Tidal Disruption Events in the TDAMM era

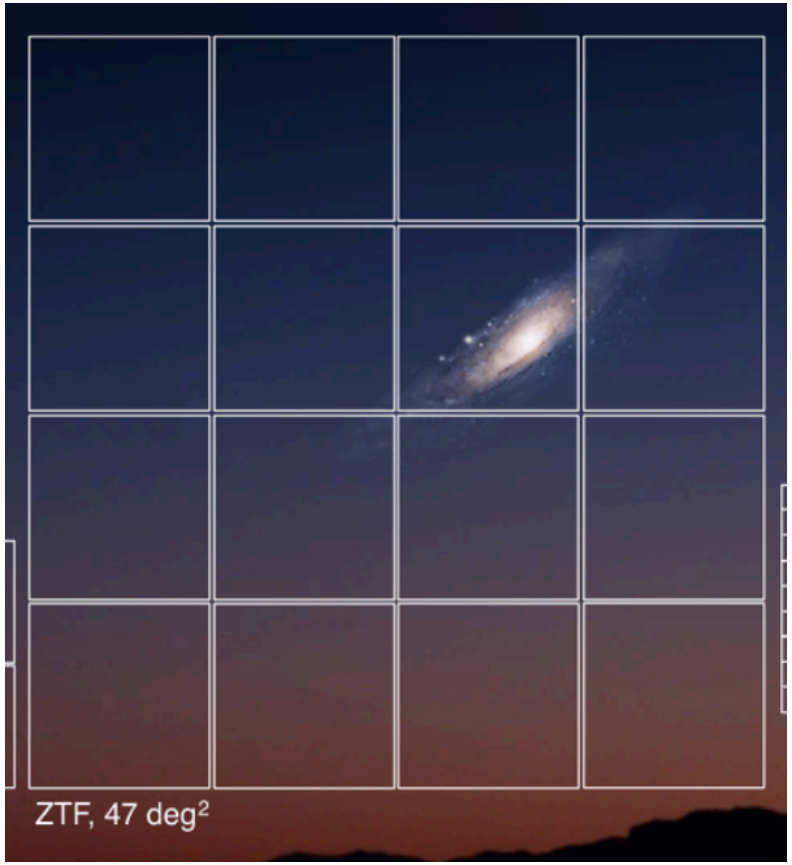
Lessons learned from ZTF

Robert Stein
Postdoctoral Scholar at Caltech
TDAMM Workshop, Annapolis, US

Caltech

How can we probe the multi-messenger emission of TDEs?

Introducing the Zwicky Transient Facility



Credit: Iair Arcavi

ZTF is an optical telescope with a 47 sq. deg. field of view

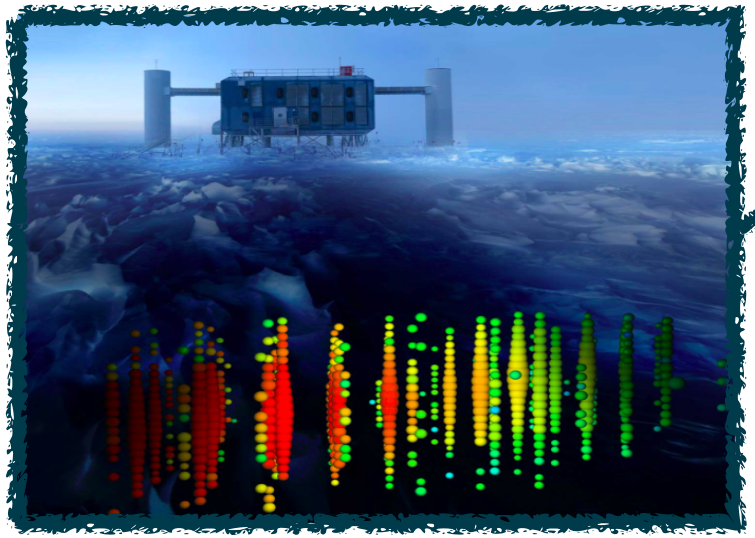
Surveys the entire northern sky every 2 nights, in g+r, as part of a public survey

The ZTF neutrino follow-up program

Stein et al. 2022

Credit: Iair Arcavi

~500k objects per night



Credit: IceCube

Neutrino direction and time

Find counterpart?

Trigger Follow-Up

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Stein et al. 2022

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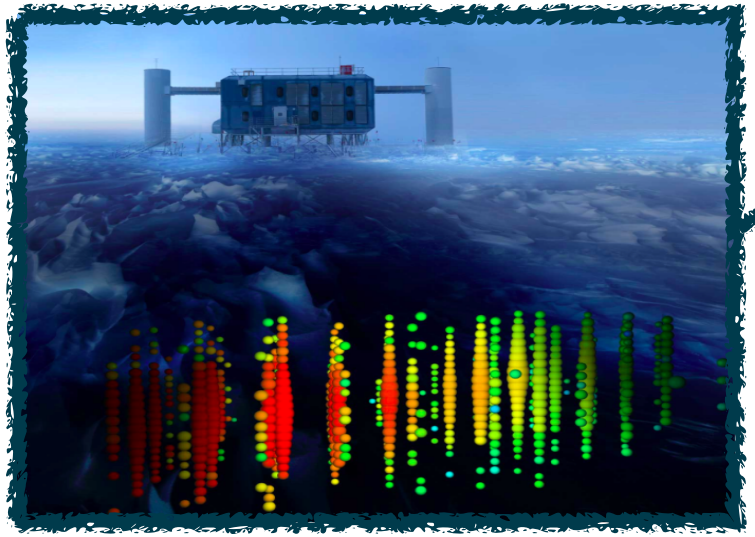
~500k objects per night

Reject stars, asteroids, planets

Correlate

Spectroscopically classify few remaining objects



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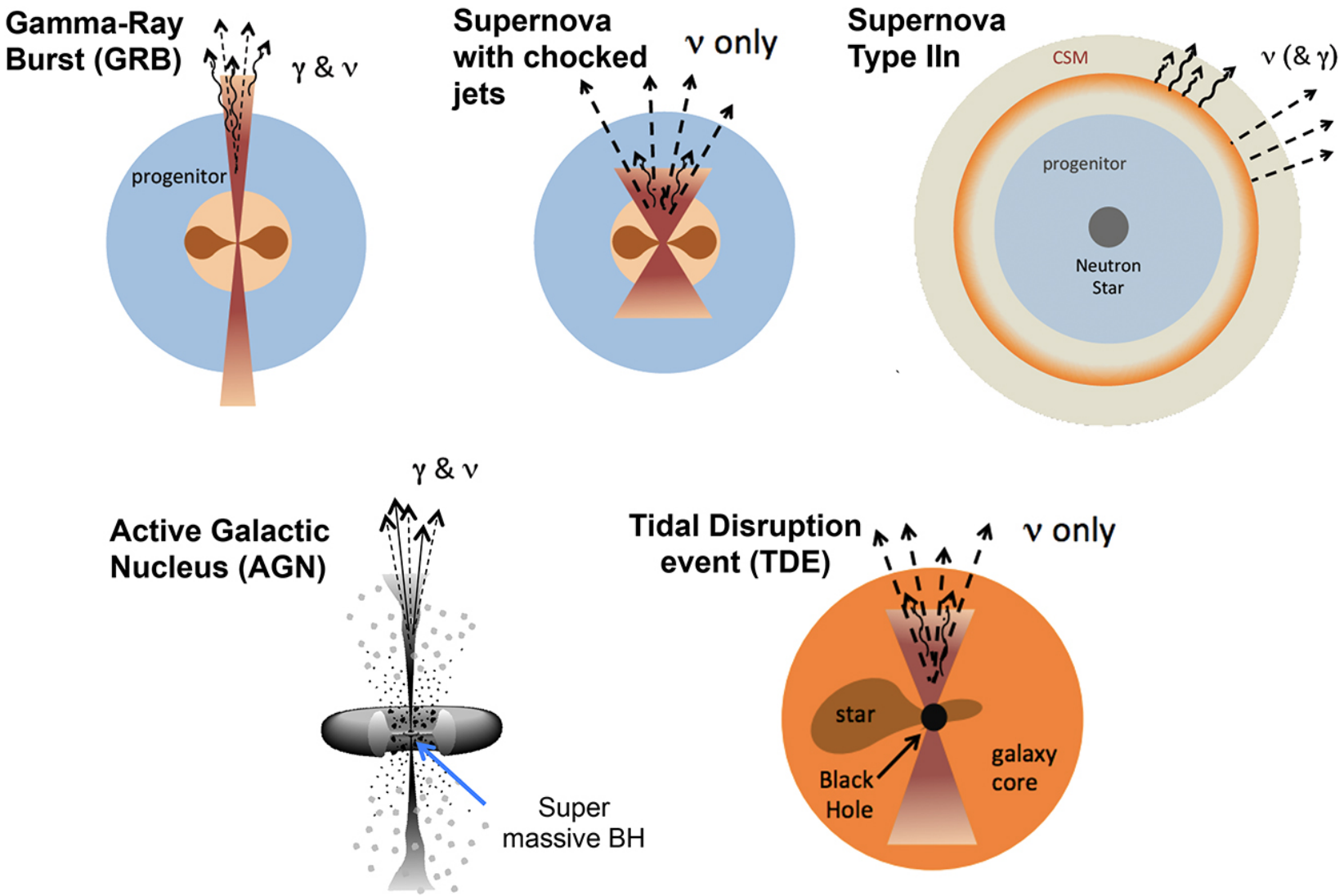
Neutrino direction and time

Find counterpart?

Trigger Follow-Up

What are we looking for?

Bartos and Kowalski 2017



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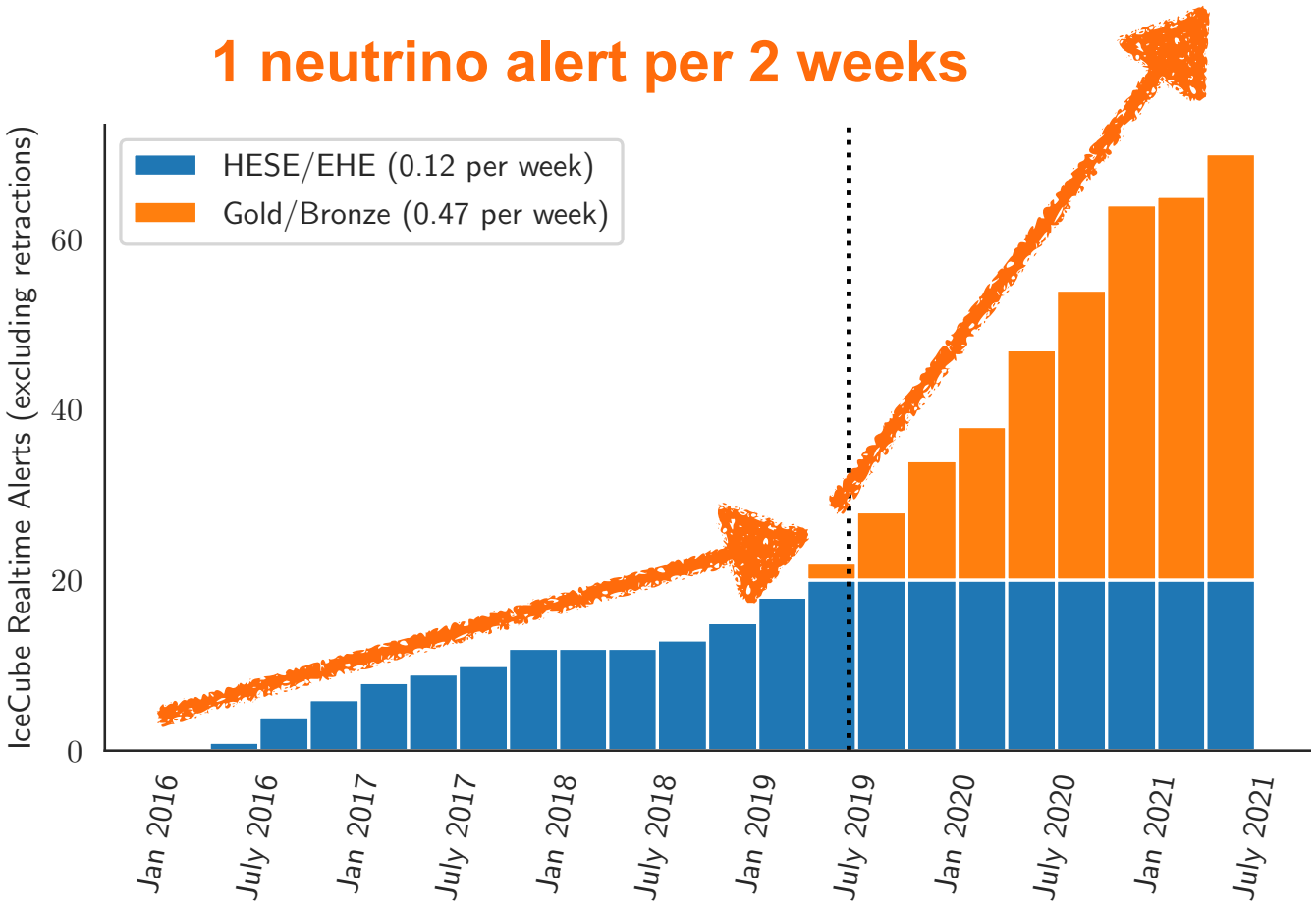
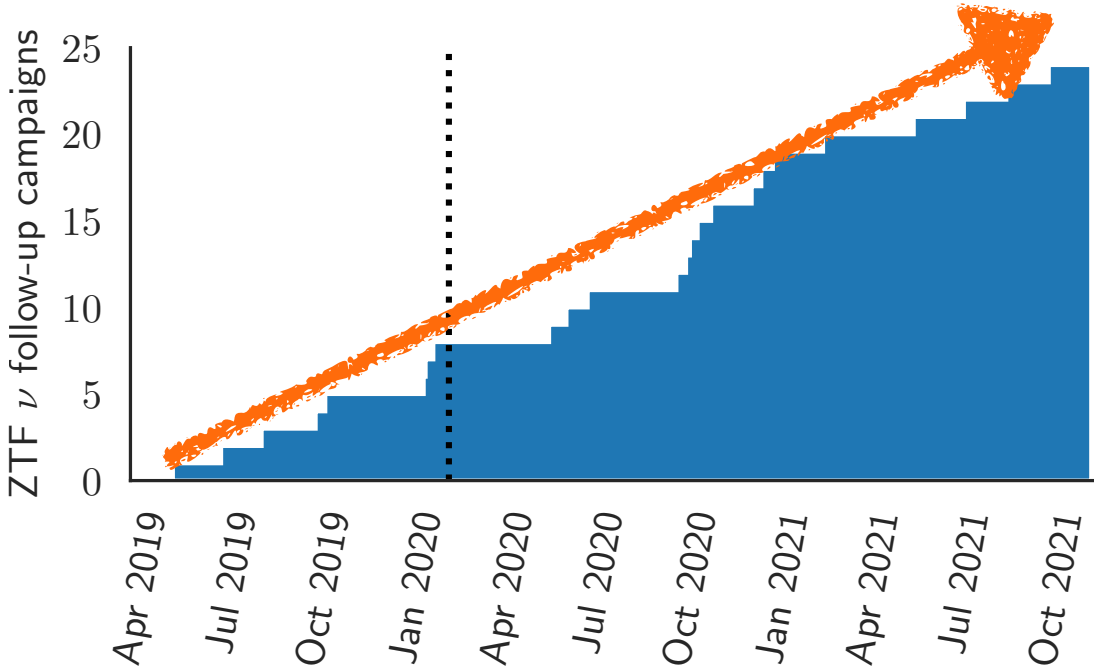
Some statistics…

1 neutrino alert per 2 weeks

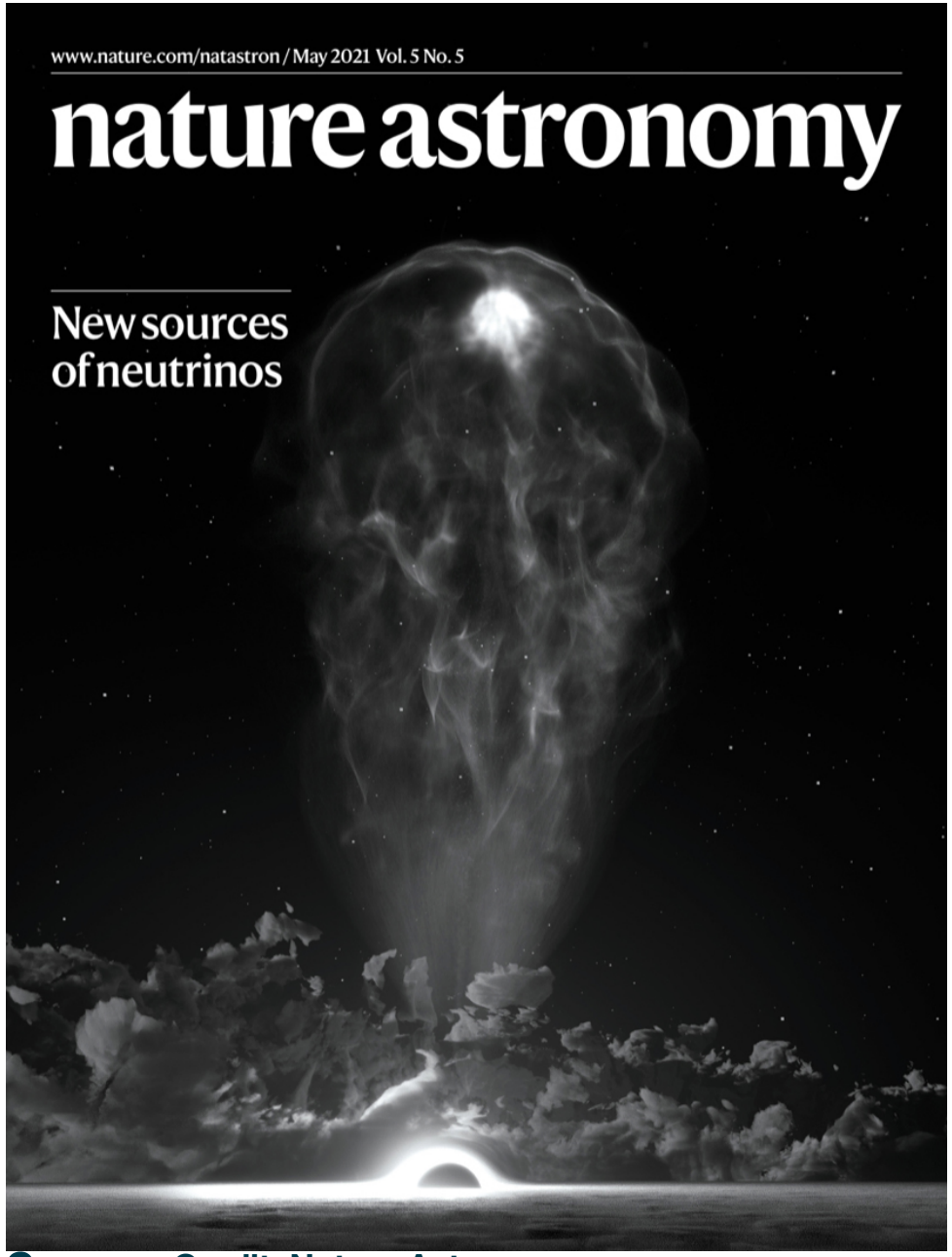


1 ZTF campaign per 5 weeks



Stein et al. 2022

Two TDEs coincident with neutrinos



Credit: Nature Astronomy

ARTICLES
https://doi.org/10.1038/s41550-020-01295-8
nature astronomy
Check for updates

A tidal disruption event coincident with a high-energy neutrino

Stein et al. 2021

Featured in Physics | Editors' Suggestion

Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino

Simeon Reusch *et al.*
Phys. Rev. Lett. **128**, 221101 – Published 3 June 2022

Physics See Focus story: Neutrinos from a Black Hole Snack

What did we learn from ZTF?

Neutrino follow-up works as a method -> Using ~dozens of multi-wavelength follow-up campaigns, you can probe a ~10%-level contribution to the astrophysical neutrino flux.

Performing realtime searches enables prompt and flexible multi-wavelength observations to characterise individual sources.

Theoretical models, informed by both population data and this single-object data, are compatible with neutrino emission from TDEs.

What do we need to enable multi-messenger follow-up?

The ZTF neutrino follow-up program

Stein et al. 2022

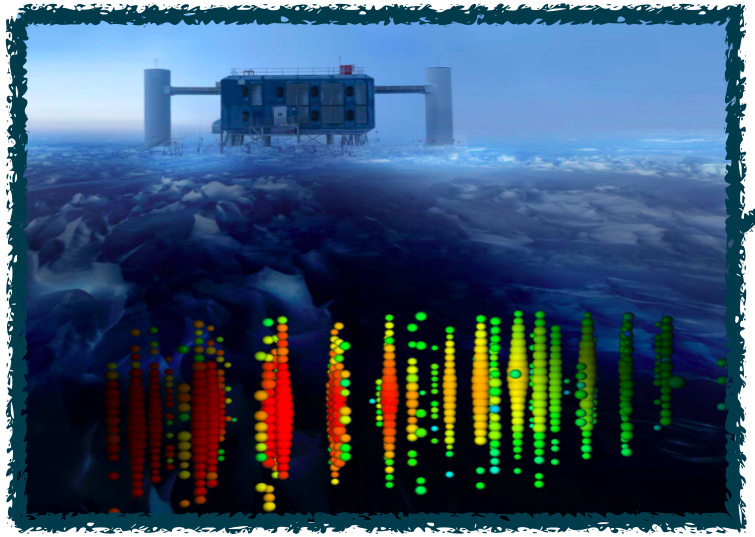
Credit: Iair Arcavi

~500k objects per night

Reject stars, asteroids, planets

Correlate

Spectroscopically classify few remaining objects



Credit: IceCube

Neutrino direction and time

Find counterpart?

Trigger Follow-Up

Any neutrino follow-up program

Stein et al. 2022

Telescope to find candidates

Pipeline to select candidates that are:

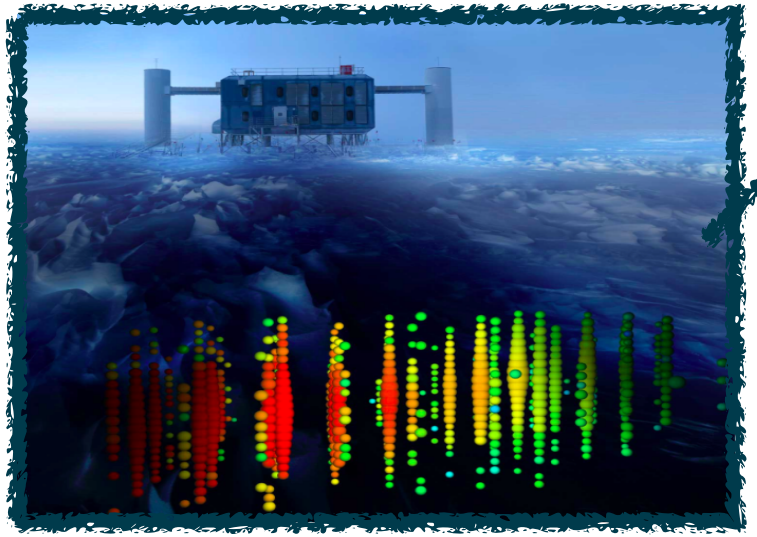
- Spatially/temporally coincident
- Likely astrophysical
- Belong to populations which could emit neutrinos

Spectroscopically classify few remaining objects

Find counterpart?

Trigger Follow-Up

Neutrino direction and time



12 Credit: IceCube

Caltech

Any neutrino follow-up program

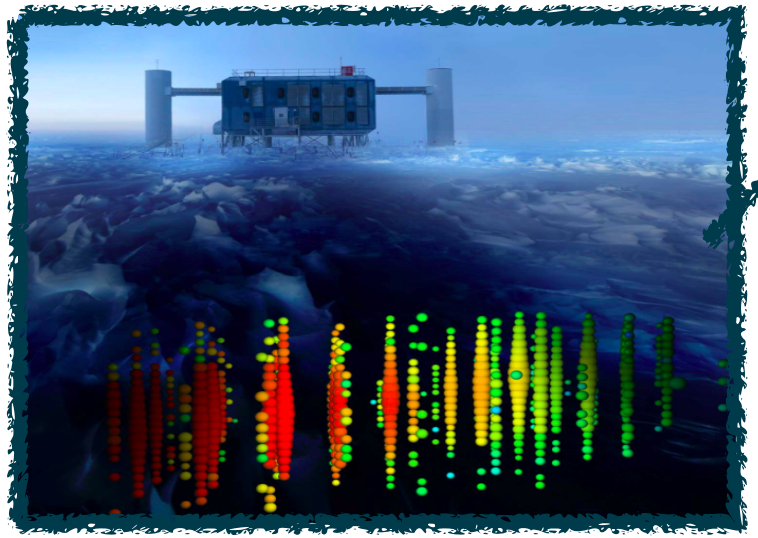
Stein et al. 2022

Telescope to find

Pipeline to select candidates that are:

- Spatially/temporally coincident

1: Prompt and reliable neutrino information is the prerequisite for all downstream multi-messenger analysis. Need accurate localisations, and useful information to prioritise "better" (=more astrophysical) neutrino alerts.



Neutrino direction and time

Spectroscopically classify few remaining objects

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Trigger Follow-Up

13 Credit: IceCube

Any neutrino follow-up program

Stein et al. 2022

Telescope to find candidates

Pipeline to select candidates that are:

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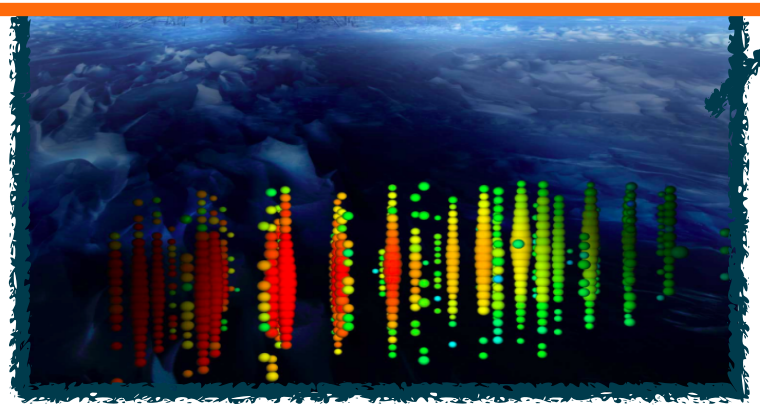
- Belong to populations which could emit neutrinos

2. Once accounting for detector systematics, neutrino "90% contours" will almost always be a few square degrees. Suitably wide-field telescopes are required to tile these regions and identify possible EM counterparts.



Neutrino direction and time

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Any neutrino follow-up program

Stein et al. 2022

Telescope to find candidates

Pipeline to select candidates that are:

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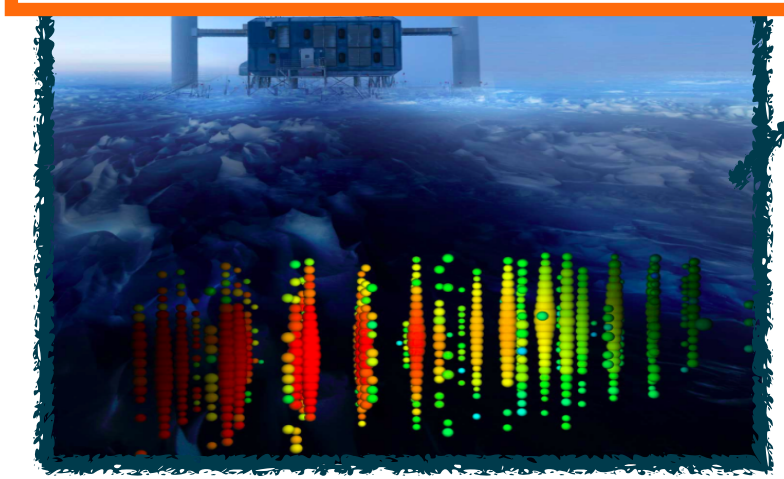
3. Pipelines are needed to select candidates. This is primarily done though algorithmic filtering, ML, catalogue matching. Public survey data is invaluable here.



Credit: IceCube

Neutrino direction and time

Credit: Laurie Hatch

Find counterpart?

Trigger Follow-Up

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Stein et al. 2022

Telescope to find candidates

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Spectroscopically classify few remaining objects

4. Need dedicated spectroscopic programs to support EM follow-up.

time

Trigger Follow-Up

16 Credit: IceCube

Caltech

Any neutrino follow-up program

Stein et al. 2022

Telescope to find candidates

Pipeline to select candidates that are:

- Spatially/temporally coincident
- Likely astrophysical
- Belong to populations which could emit neutrinos

5. We require multi-wavelength observations to characterise the sources. These could be from dedicated proposals, but DDTs have also worked well. The community is currently operating a "kitchen sink" model, and that will presumably still be true in another decade.

Neutrino direction and time

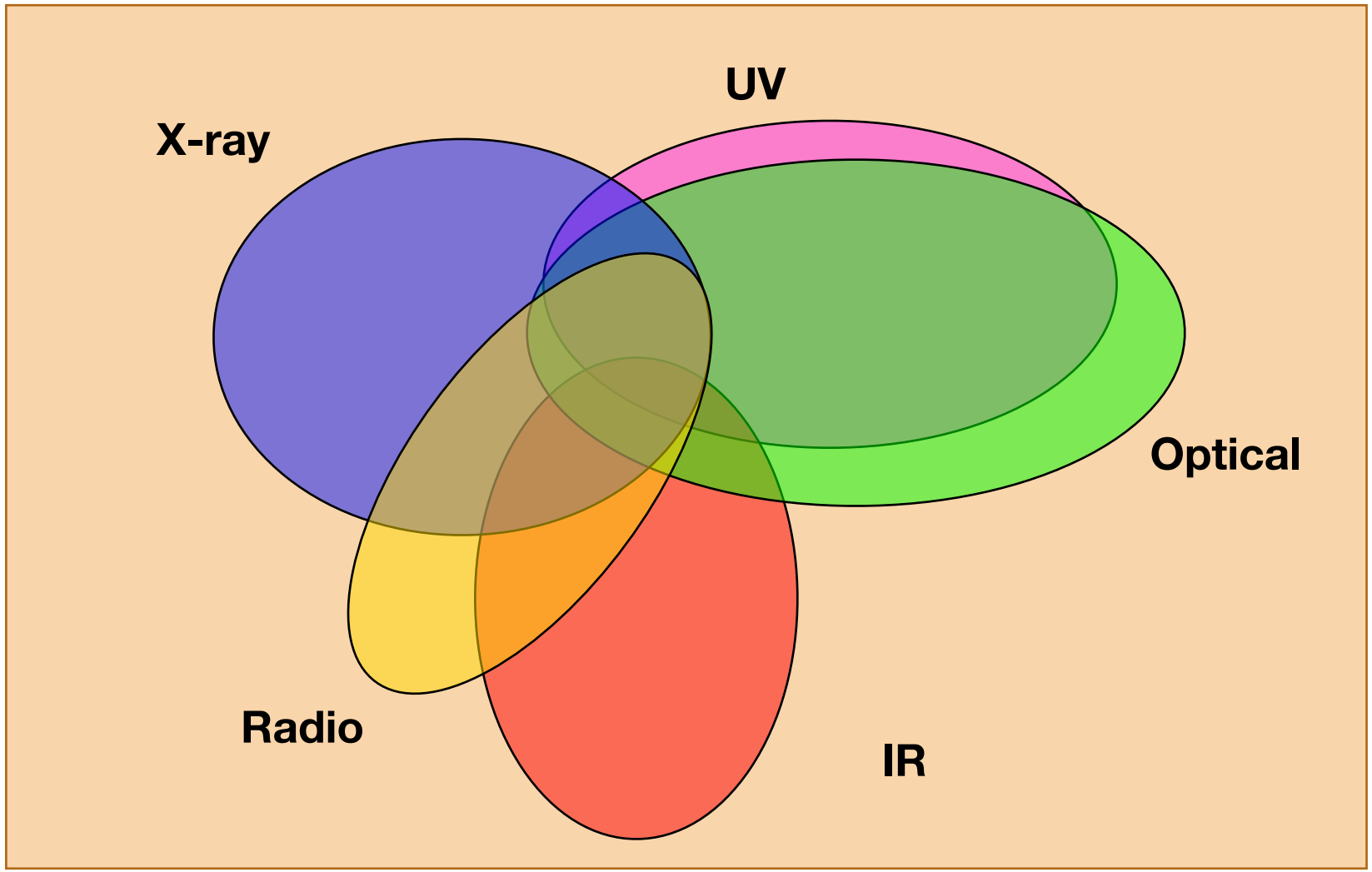
Find counterpart?

Trigger Follow-Up

17 Credit: IceCube

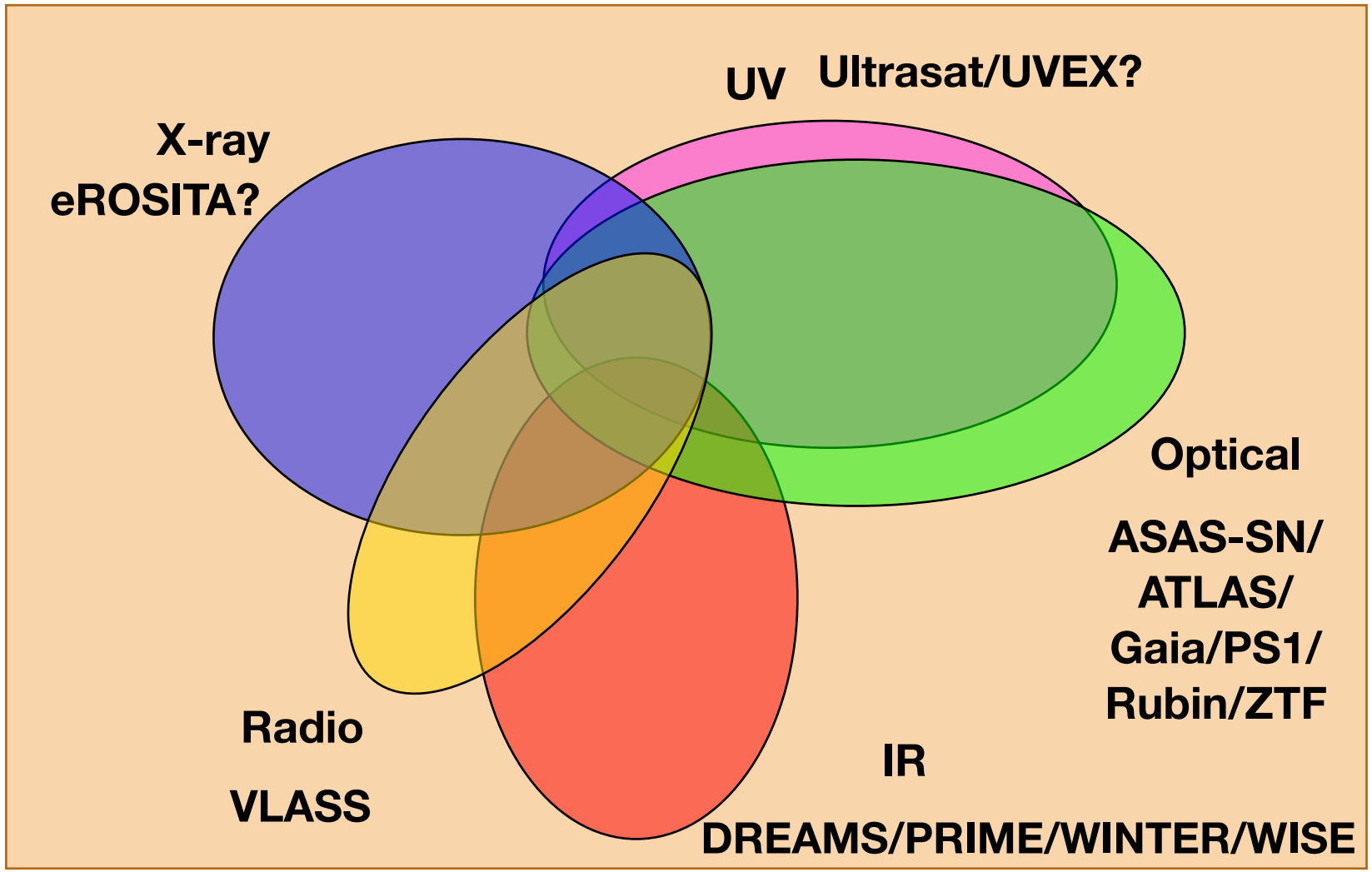
Beyond Optical Follow-Up

Towards a pan-chromatic view of TDEs



Not to scale (yet!)

Towards a pan-chromatic view of TDEs



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Systematic searches are possible. Need wide-field surveys for each wavelength!

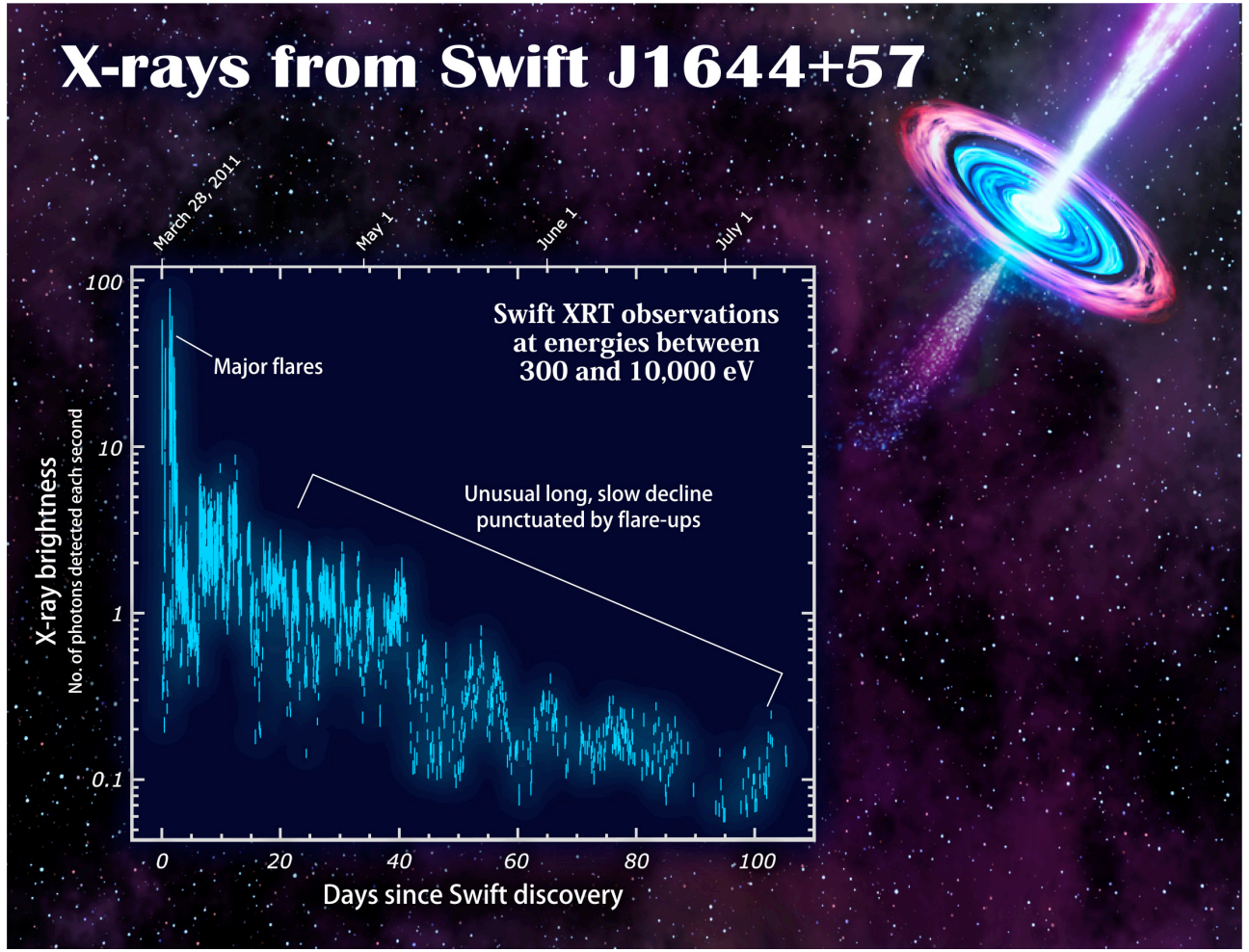
WINTER: Wide-field InfraRed Transient Explorer

Credit: Robert Stein

WINTER will do a J-band survey at ~monthly cadence, AND dedicated neutrino follow-up!

Thinking outside the box

The view from 2011



Credit: NASA

The New York Times

OBSERVATORY

In Celestial Twist, Black Hole Swallows a Dying Star

Give this article

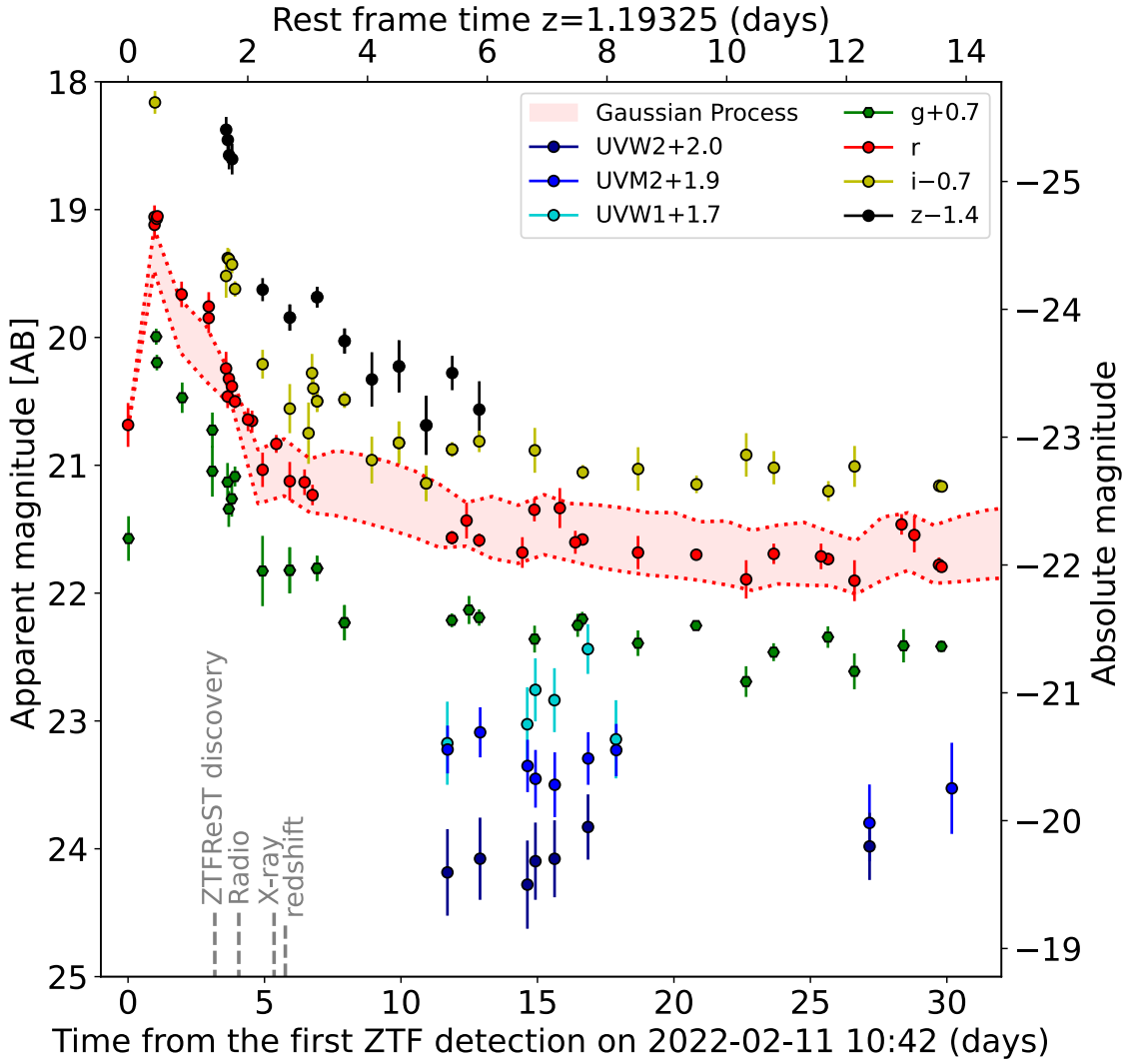
By Sindya N. Bhanoo
June 16, 2011

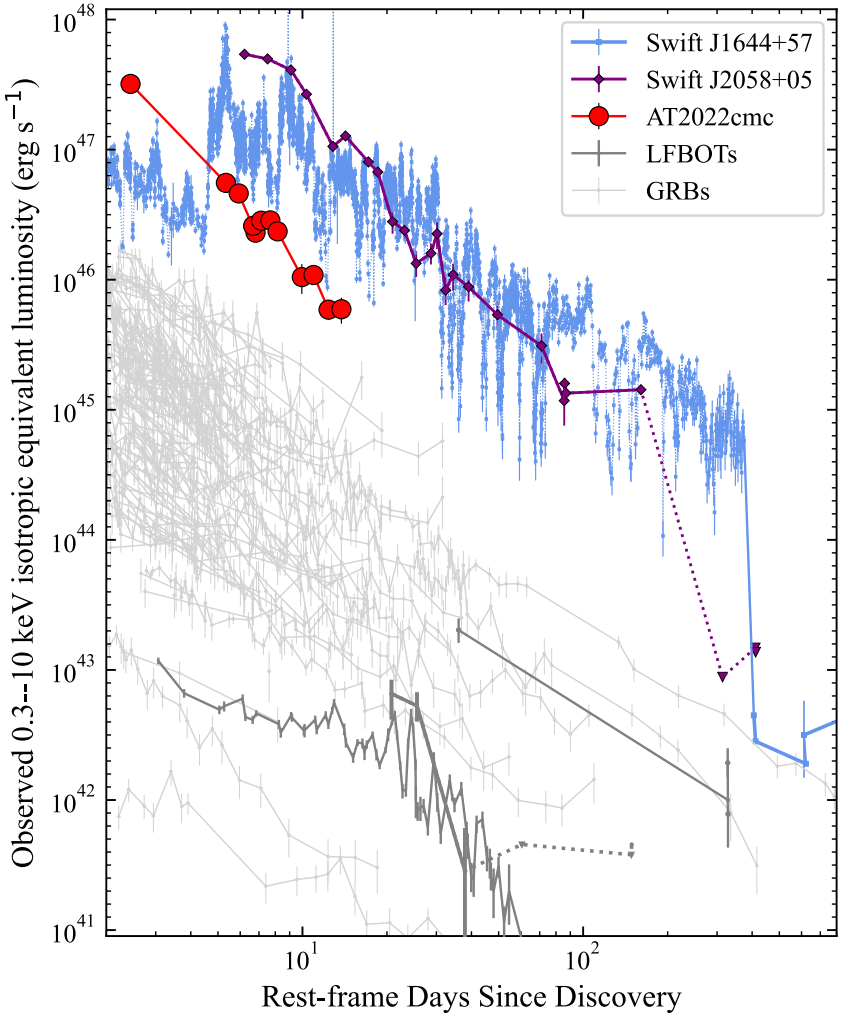
In what sounds like a one of a kind murder mystery, a dying star has fallen into a black hole and been ripped apart.

The event, which was observed on March 28, was originally thought to be a gamma ray burst from a collapsing star, but researchers suspected something more sinister was at play. Their findings appear in a pair of papers published online by the journal Science.

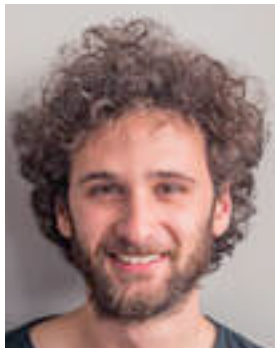
Jetted TDEs are "the dog that didn't bark"

Back to the future: An optically-selected on-axis “jetted TDE”





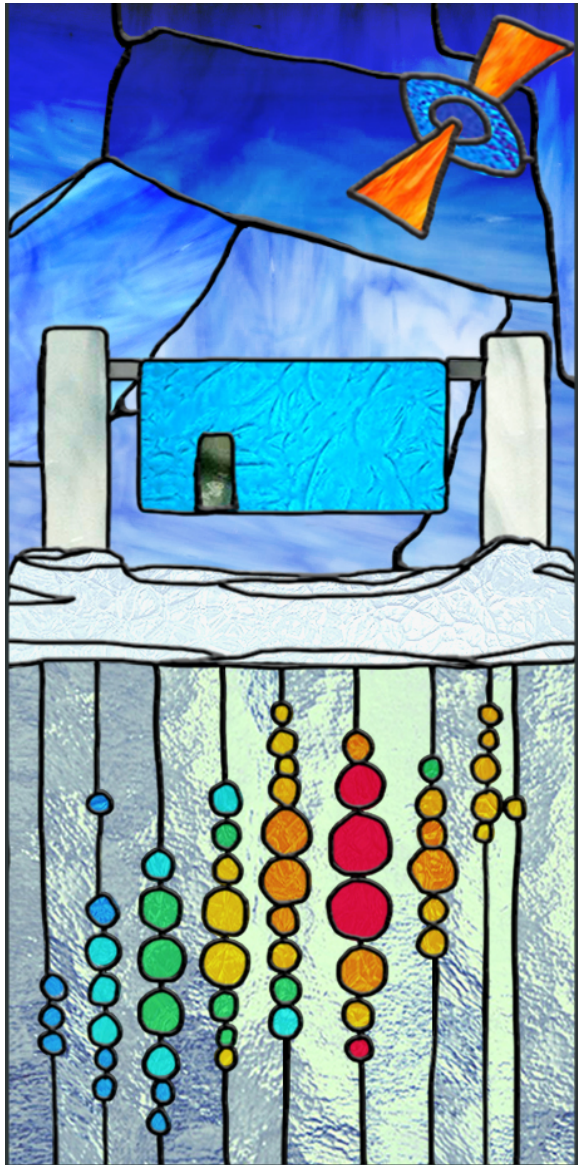
Andreoni et al. submitted



Summary

Summary

- TDE science has had a great decade, let's hope the next one is just as fruitful!
- Neutrino follow-up can probe the multi-messenger emission of TDEs, but requires an integrated TDA ecosystem.
- We need to better understand the intersecting multi-wavelength properties of TDEs. Requires wide-field surveys.
- It was an unexpectedly slow decade for relativistic TDEs. Optically-selected AT2022cmc has provided an exciting leap forward, and suggests we need to pay more attention to "rapid transients".

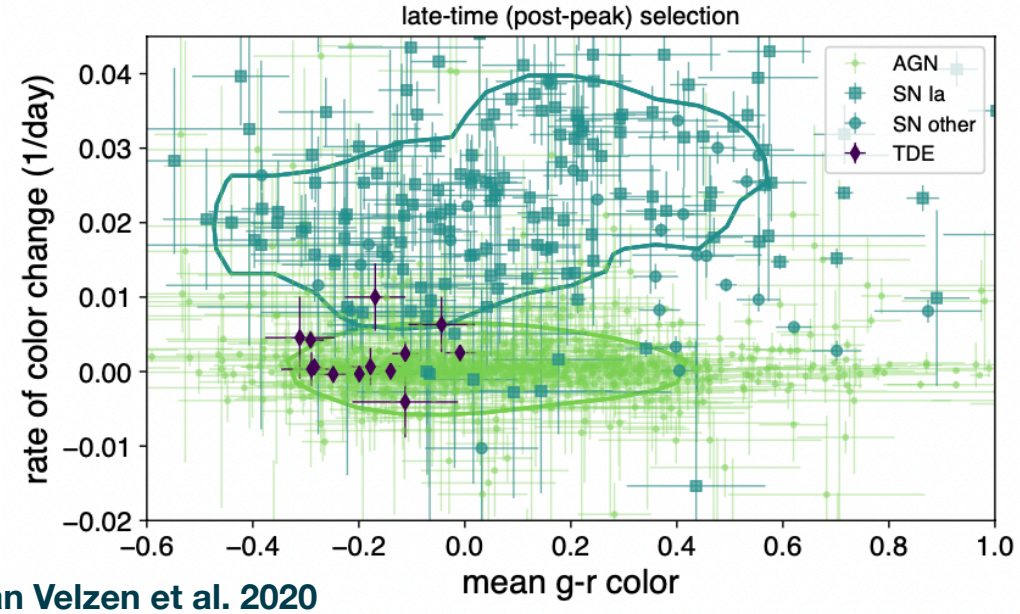


Credit: IceCube

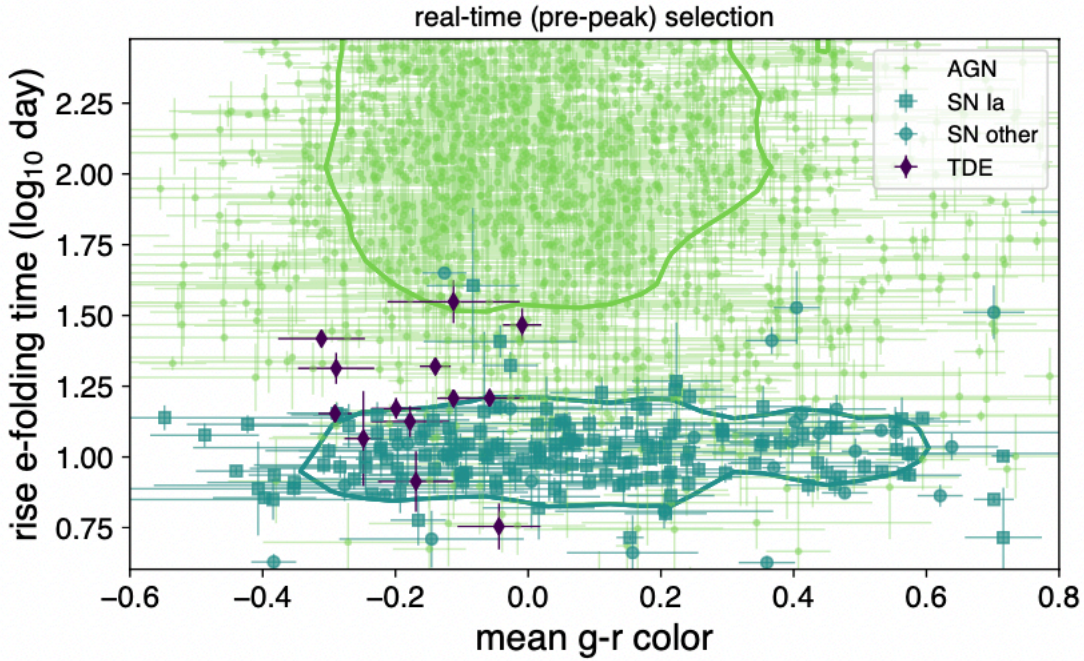
Backup

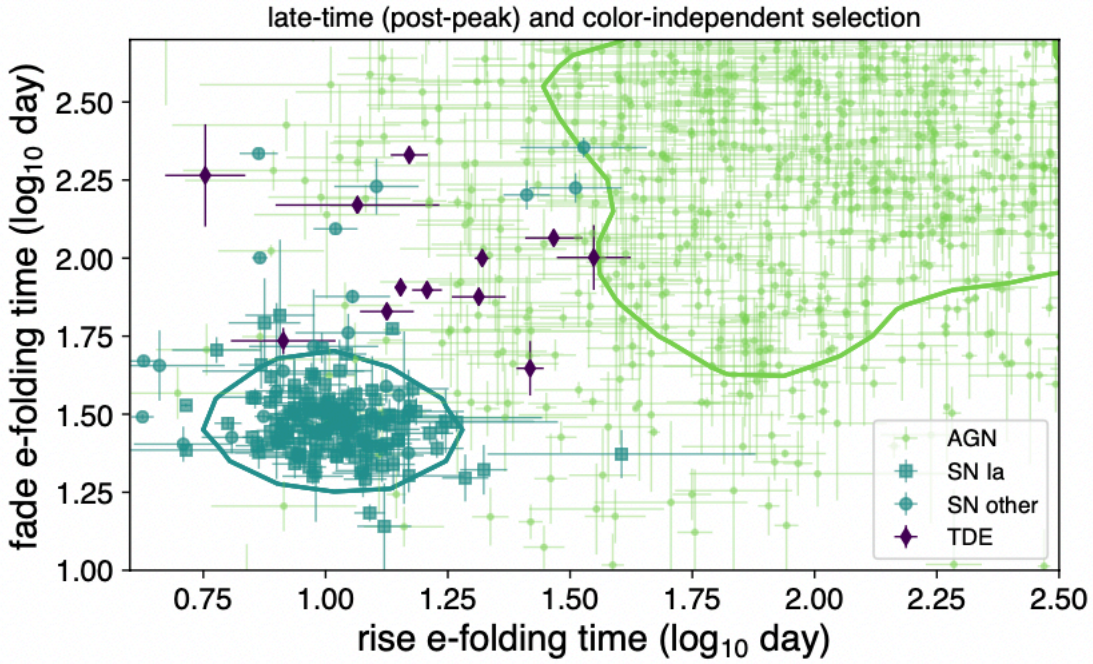
Embracing diversity in TDEs

How does ZTF find a TDE?

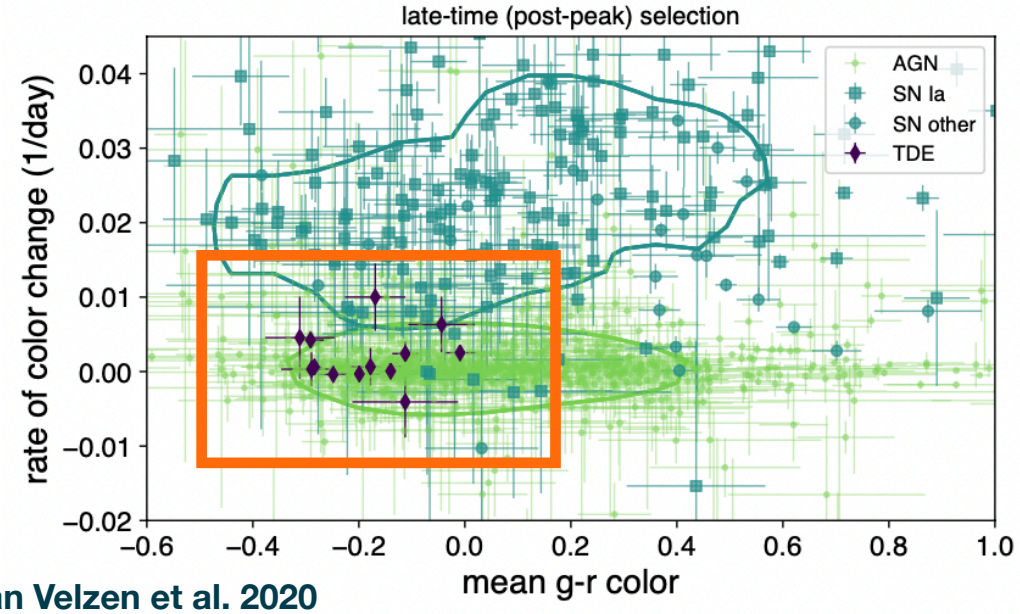


Van Velzen et al. 2020





How does ZTF find a TDE?



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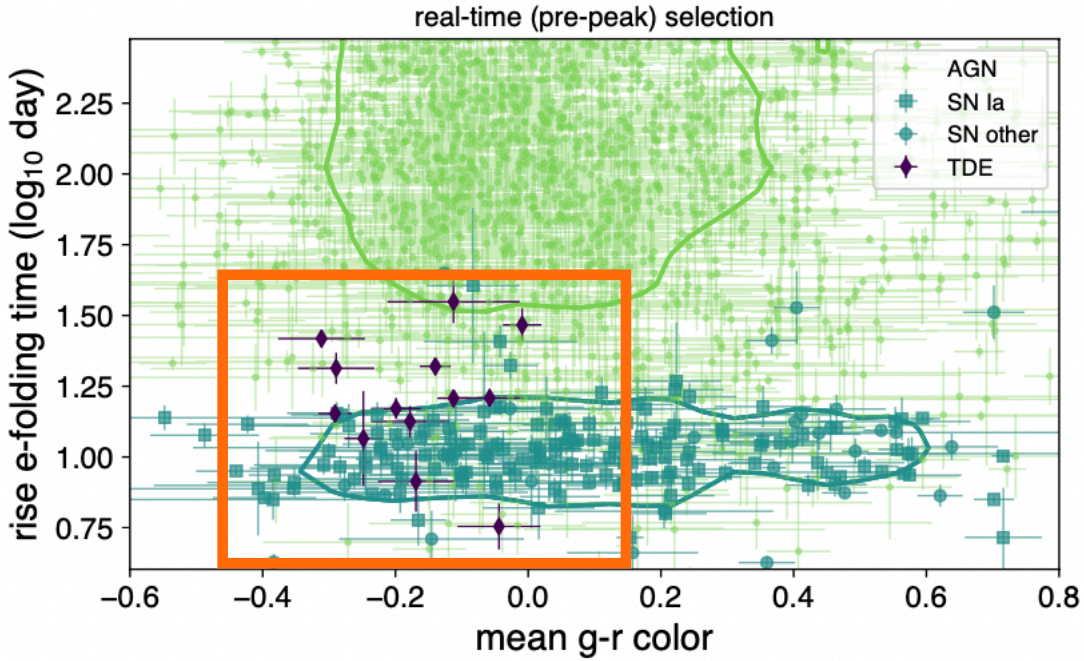
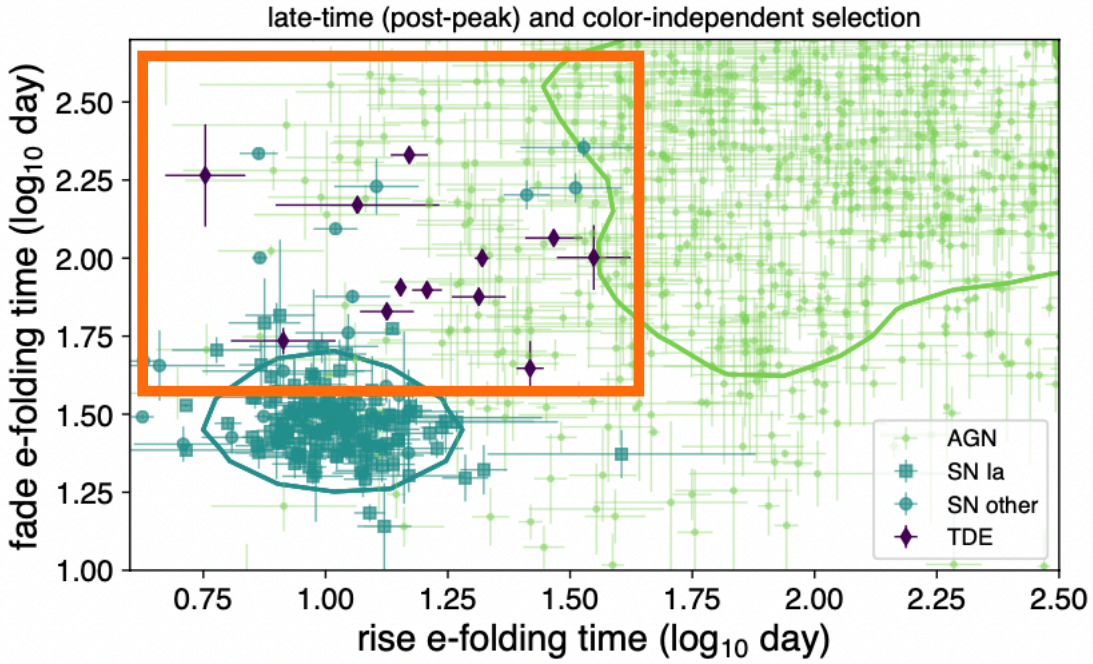
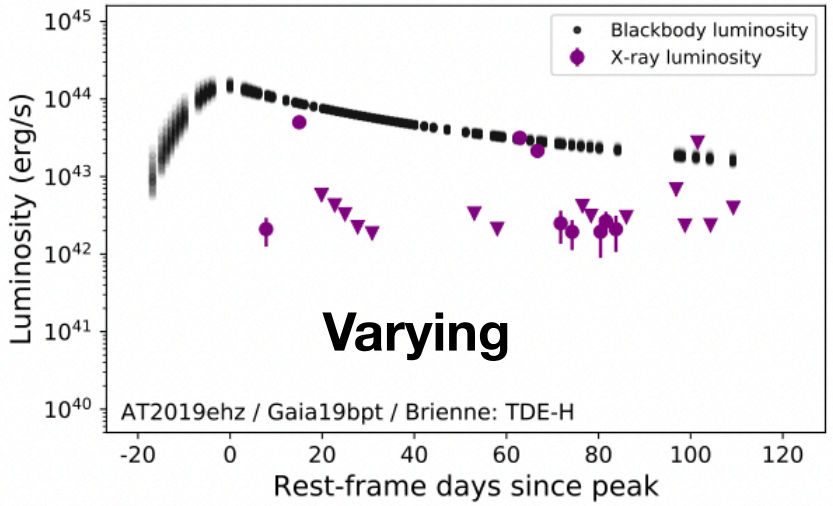


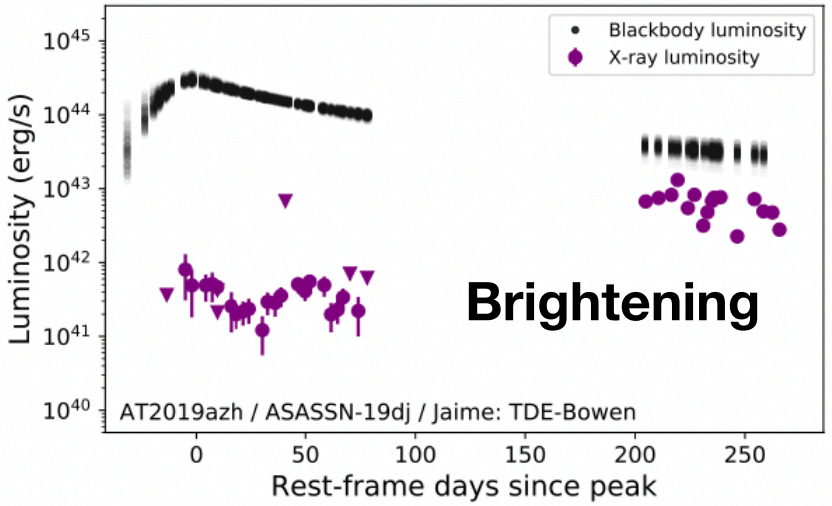


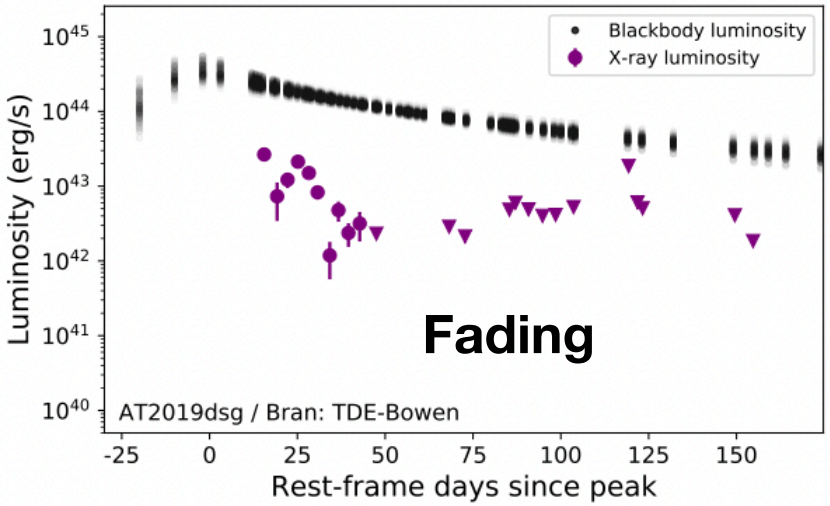
ZTF operates a "Rubin-style" selection function to select TDE candidates with relatively high purity, yielding a systematic optical sample

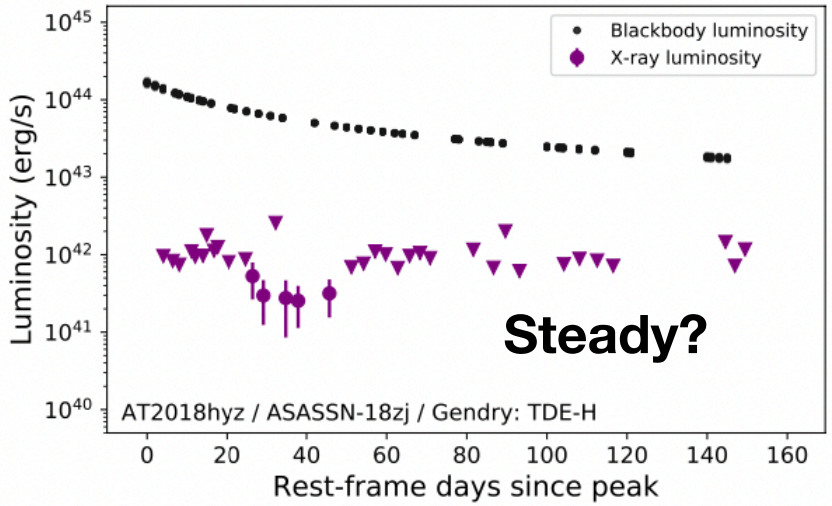
Case Study: X-ray properties of 17 optical TDEs

Van Velzen et al. 2020



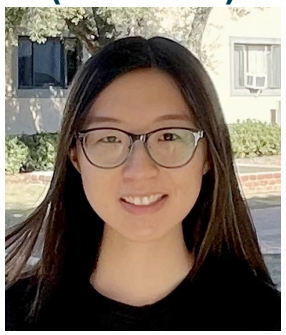


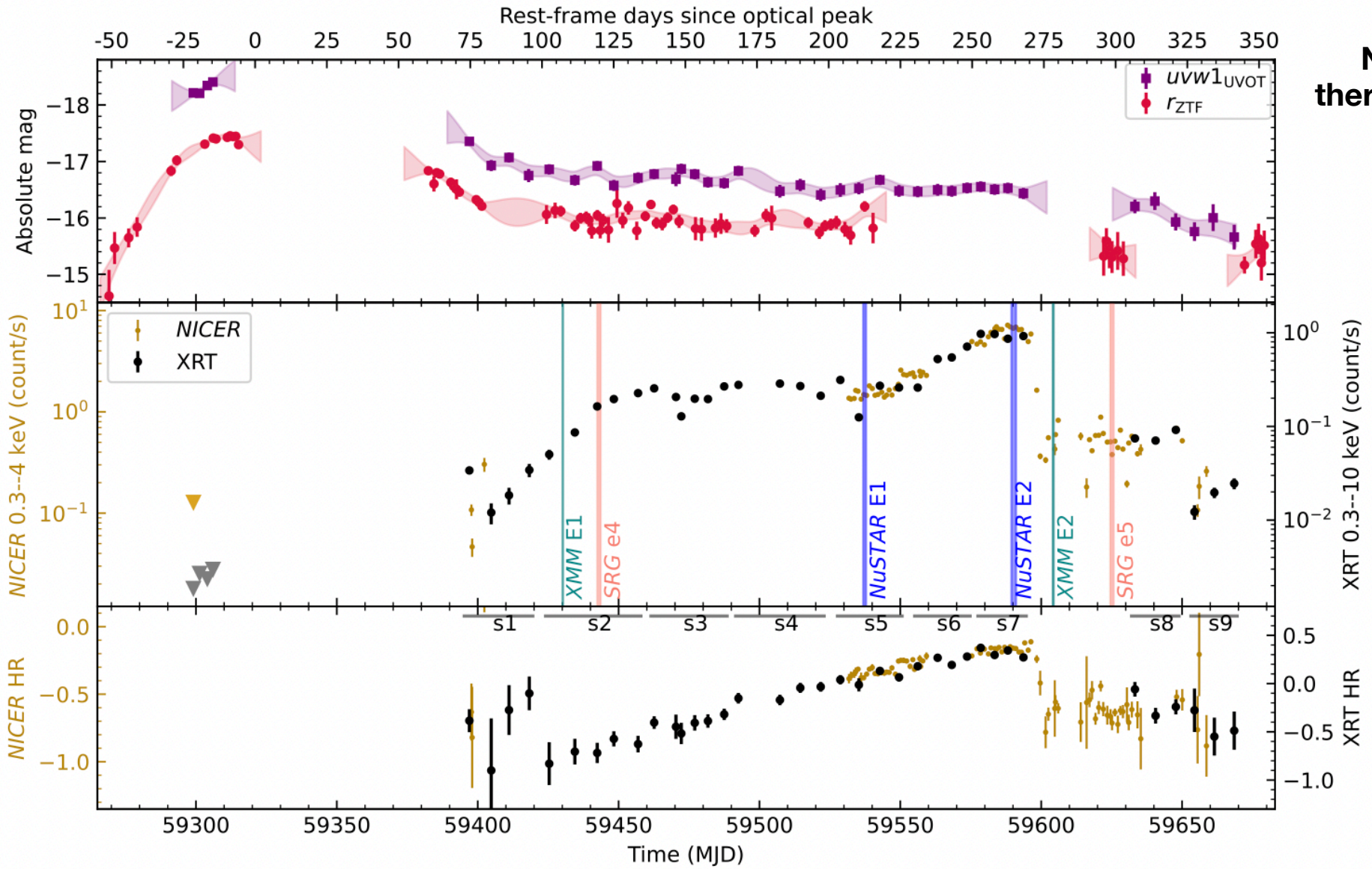




More recently: AT2021ehb with dramatic X-ray/HR evolution

Yao et al. 2022 (submitted)



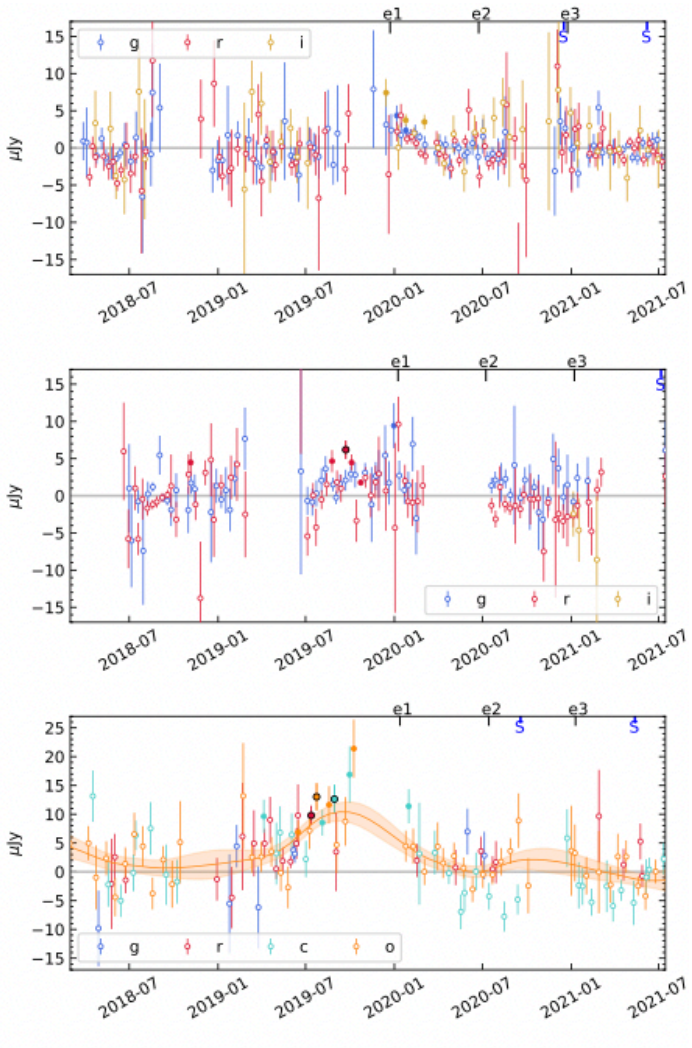


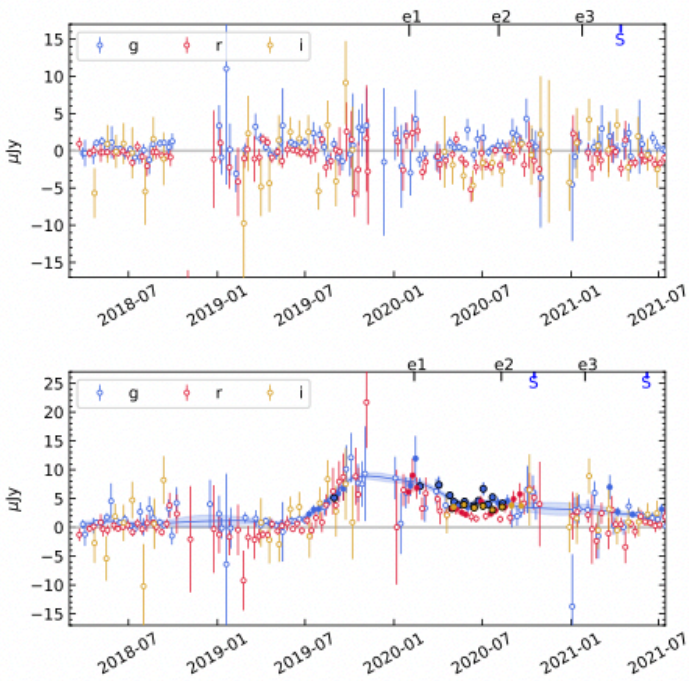
Not just a soft thermal component!

X-ray-selected TDEs from eROSITA tell a different story

Sazonov et al 2022.

Object (SRGE)	Optical flare peak AB mag
J135514.8+311605	$g > 21.83$
J013204.6+122236	$g > 21.51$
J153503.4+455056	$21.33 < o < 20.58$
J163831.7+534020	$g > 21.84$, $r > 21.86$
J163030.2+470125	$21.47 < g < 20.71$
J021939.9+361819	$g > 21.43$
J161001.2+330121	$g > 21.68$
J171423.6+085236	$c > 20.04$
J071310.6+725627	$g > 21.41$
J095928.6+643023	$22.40 < r < 21.64$
J091747.6+524821	$21.49 < r < 20.74$
J133053.3+734824	$g > 21.73$
J144738.4+671821	$c > 20.41$

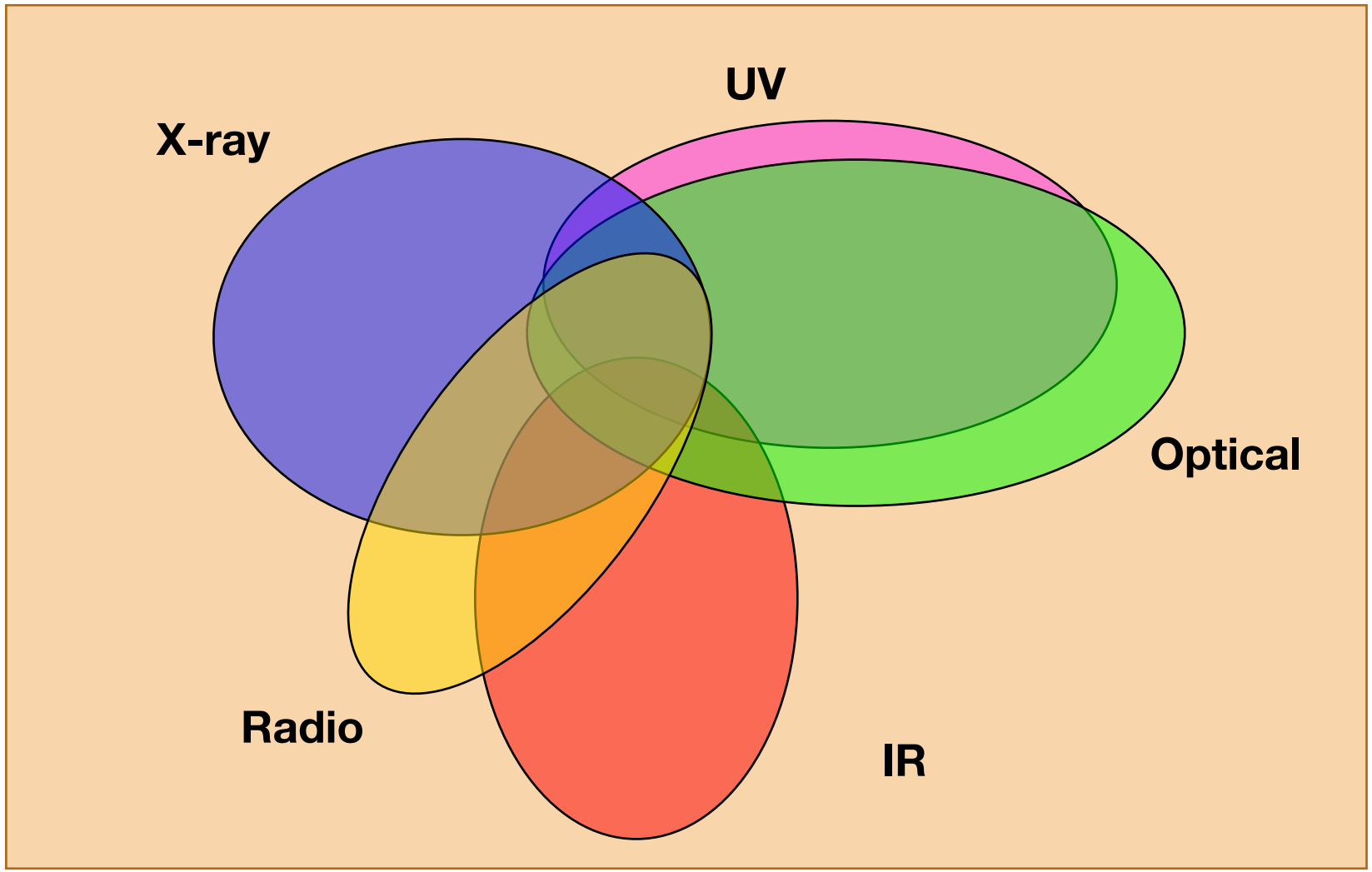




All eROSITA TDEs are optically faint, with Lopt/Lx < 0.3

Only 4/13 detected

Towards a pan-chromatic view of TDEs



Not to scale (yet!)

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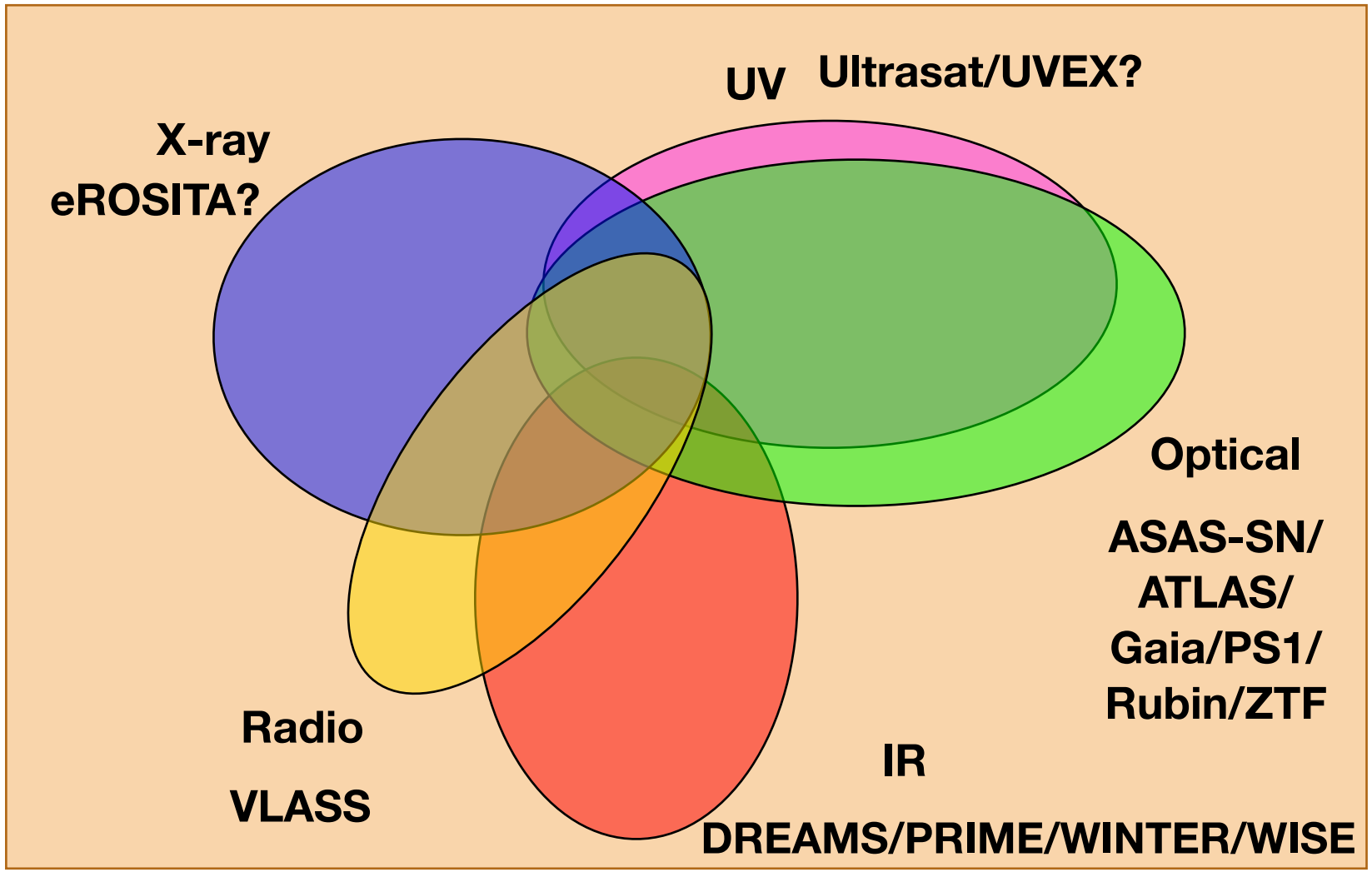


Not to scale (yet!)

Systematic searches are possible. Need wide-field surveys for each wavelength!

WINTER: Wide-field InfraRed Transient Explorer

Credit: Robert Stein

WINTER will do a J-band survey at ~monthly cadence, AND dedicated neutrino follow-up!

Bridging theory and observation

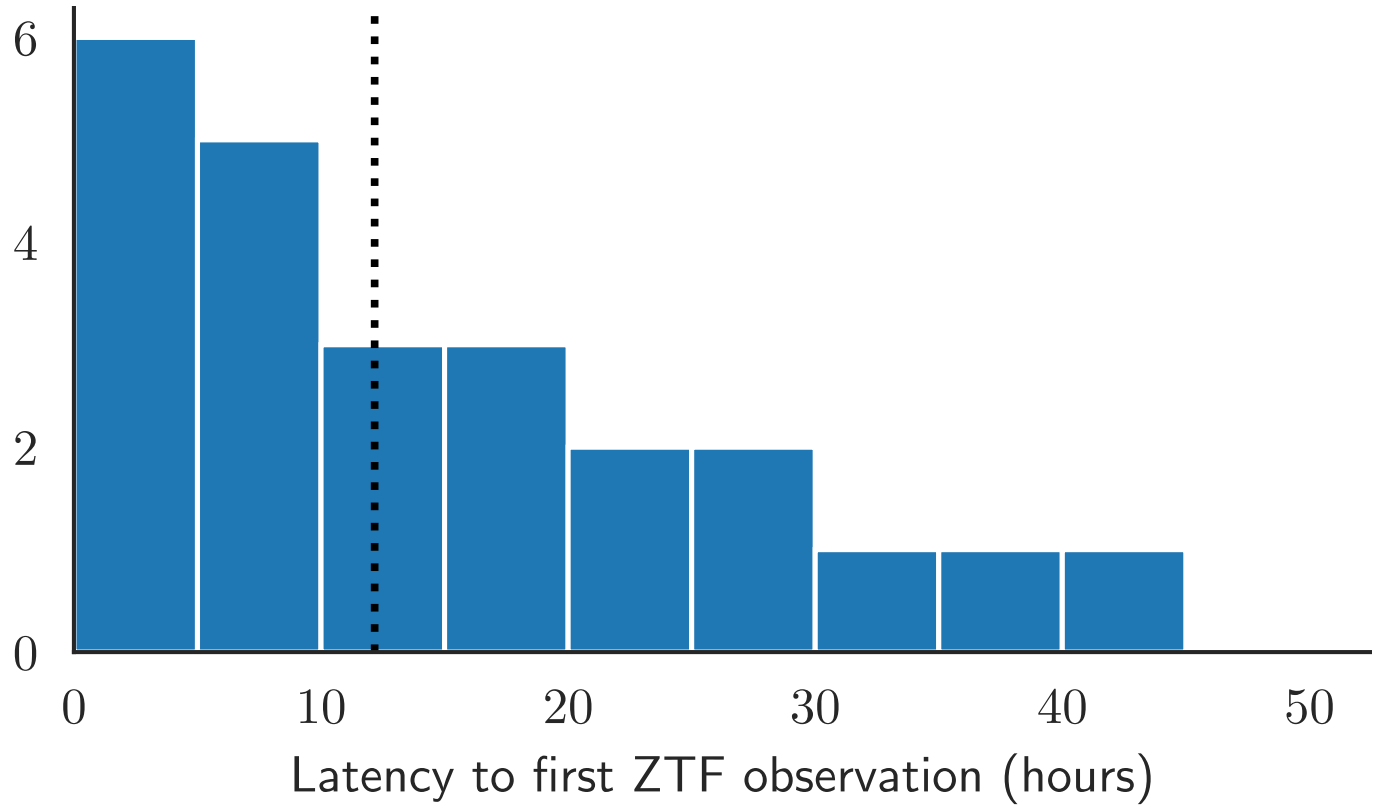
We currently lack information to inform theoretical models of TDE neutrino/CR emission.

Off the top of my head, critical open questions for theorists include:

- **What is the local rate of (all) TDEs, and of jetted TDEs specifically?**
- **How do these rates change as a function of redshift?**
- **What is the distribution of outflows, winds or jets in TDEs? How common are they? How do they vary by object?**
- **Do White-Dwarf/IMBH TDEs exist? How common are they? These in particular are studied for potential UHECR emission, but there is a substantial gap in our experimental knowledge. (We've found ~0 thus far.)**
- **How well can we distinguish a TDE in an AGN from an extreme AGN flare? What are the differences (if any) between TDE accretion and AGN accretion?**

Some statistics…

Median latency of 12 hours from neutrino detection to ZTF observation

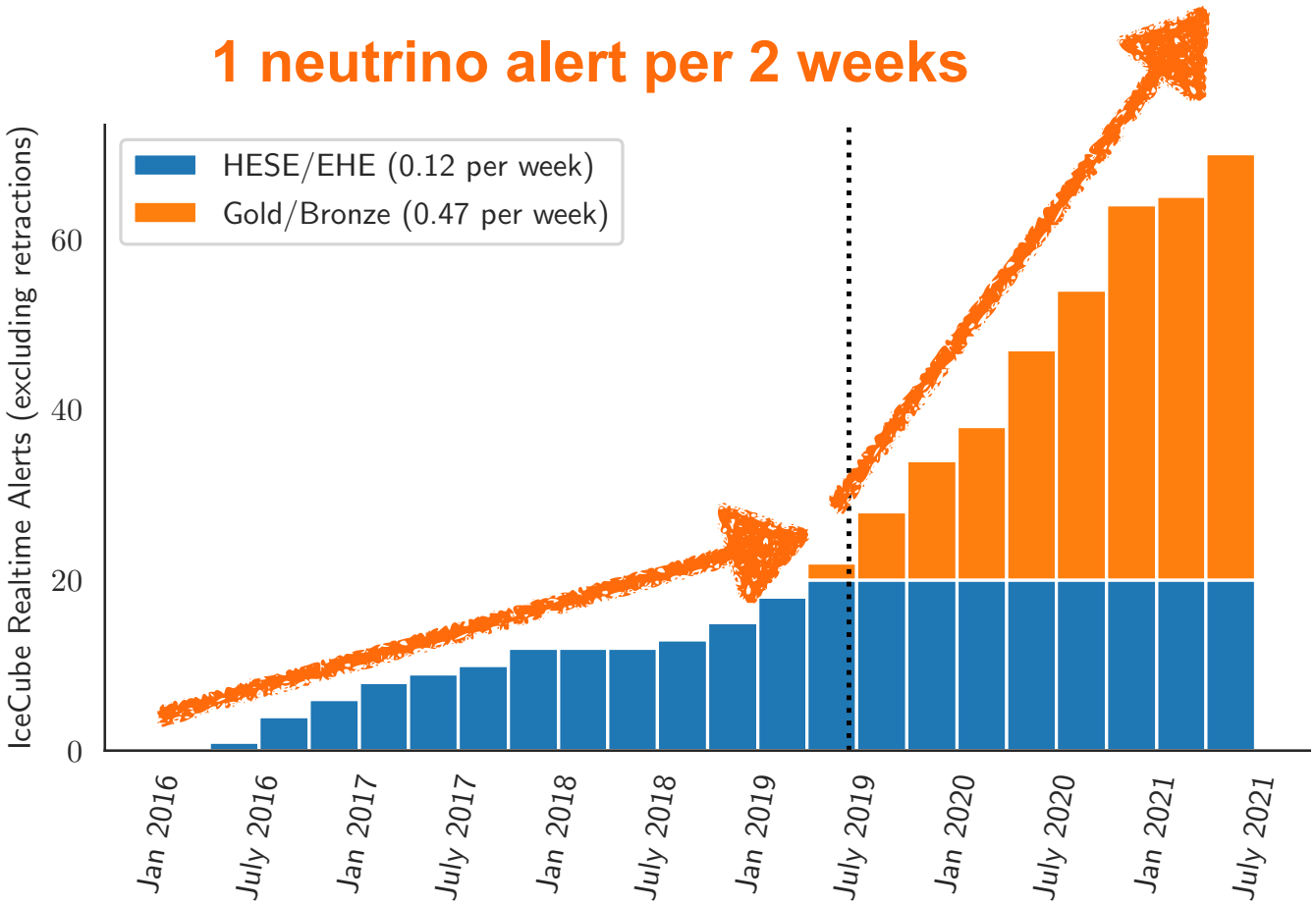


Stein et al. 2022

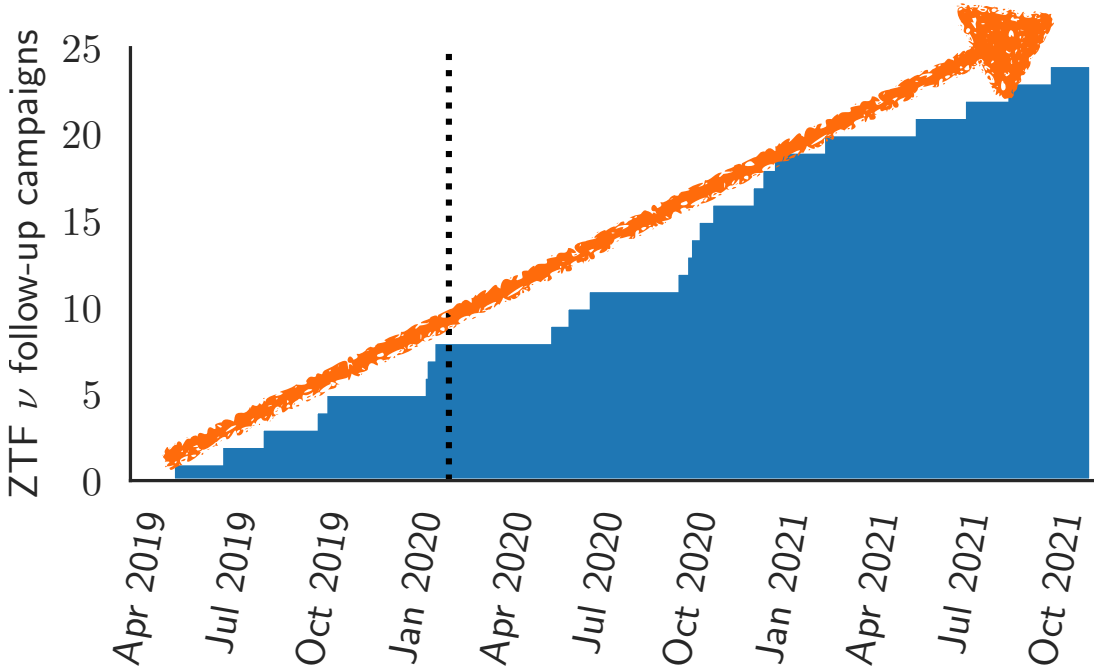
What did we find?

Some statistics…

1 neutrino alert per 2 weeks



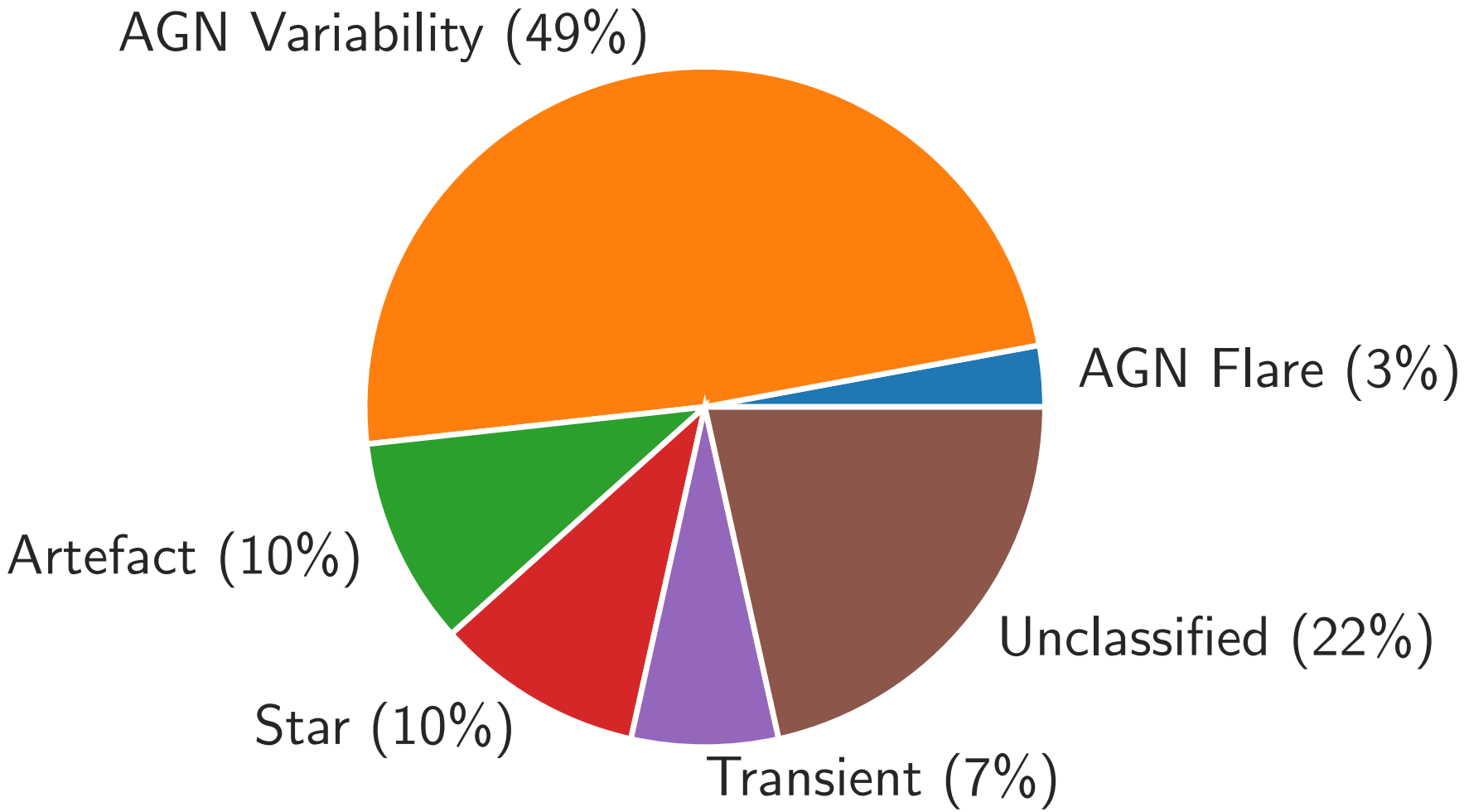
1 ZTF campaign per 5 weeks



Stein et al. 2022

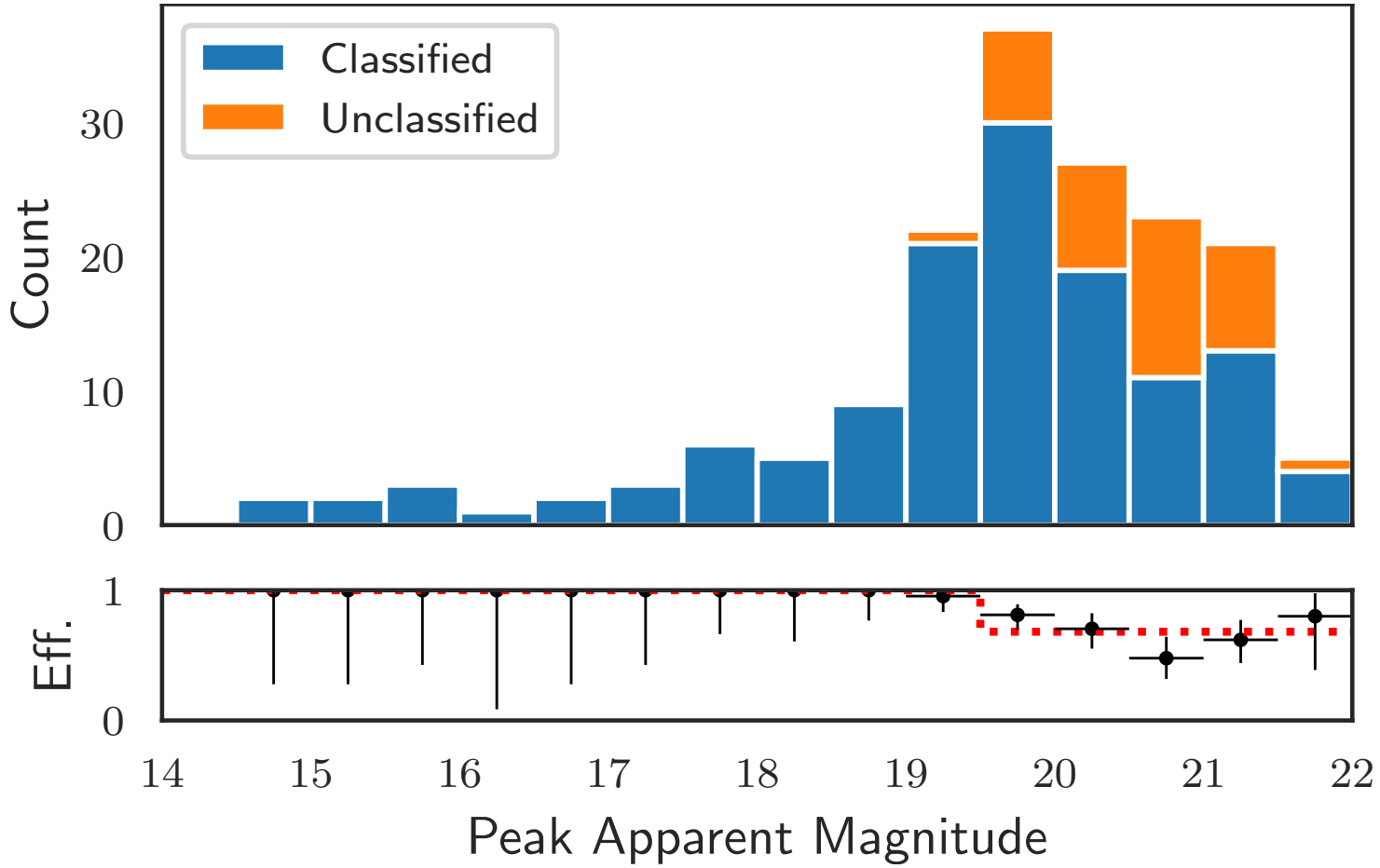
Some statistics…

Only a small fraction of 172 candidates are ultimately transients



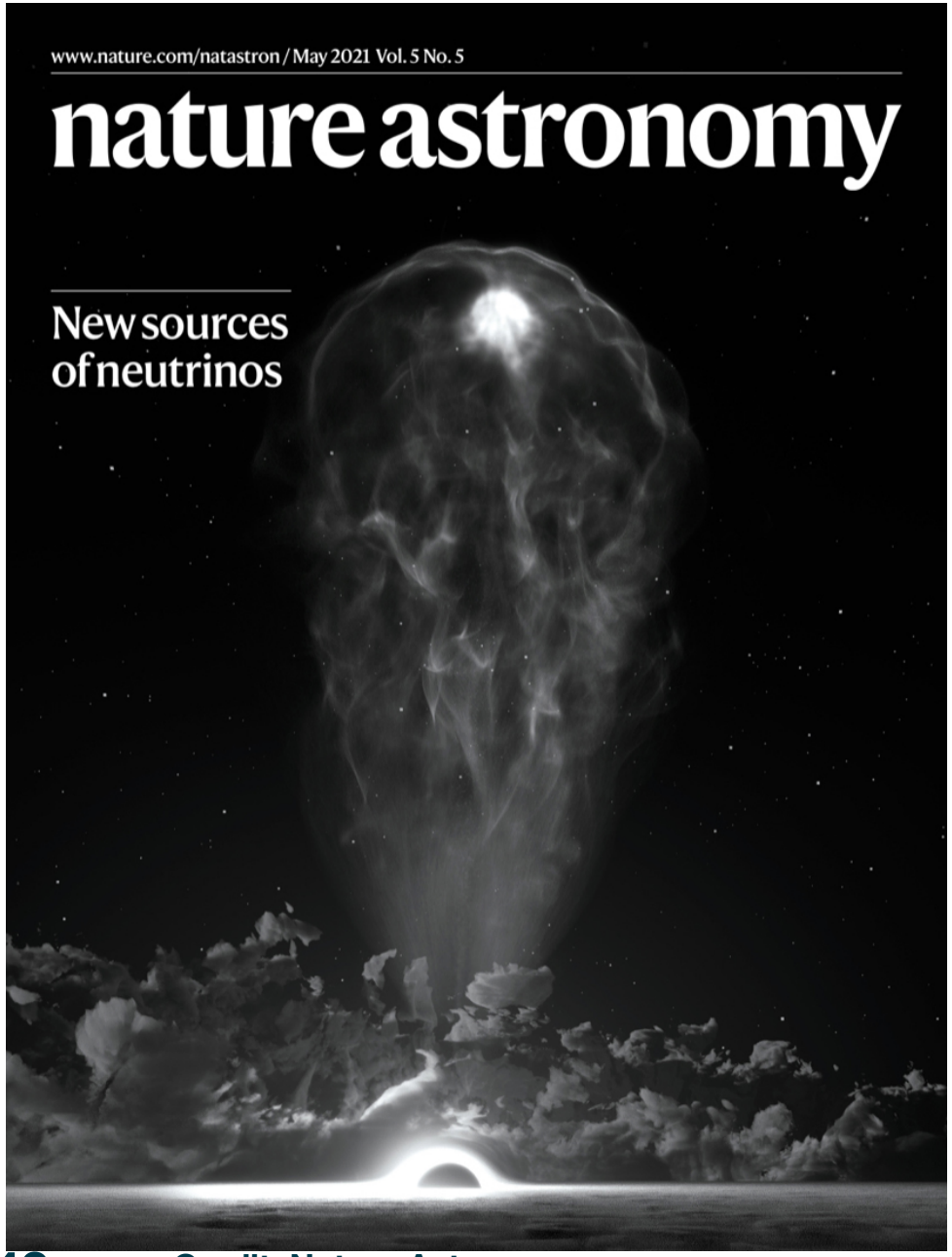
Some statistics…

We classify ~100% of bright sources and ~70% of fainter ones



Stein et al. 2022

Two TDEs coincident with neutrinos



Credit: Nature Astronomy

ARTICLES
https://doi.org/10.1038/s41550-020-01295-8
nature astronomy
Check for updates

A tidal disruption event coincident with a high-energy neutrino

Stein et al. 2021

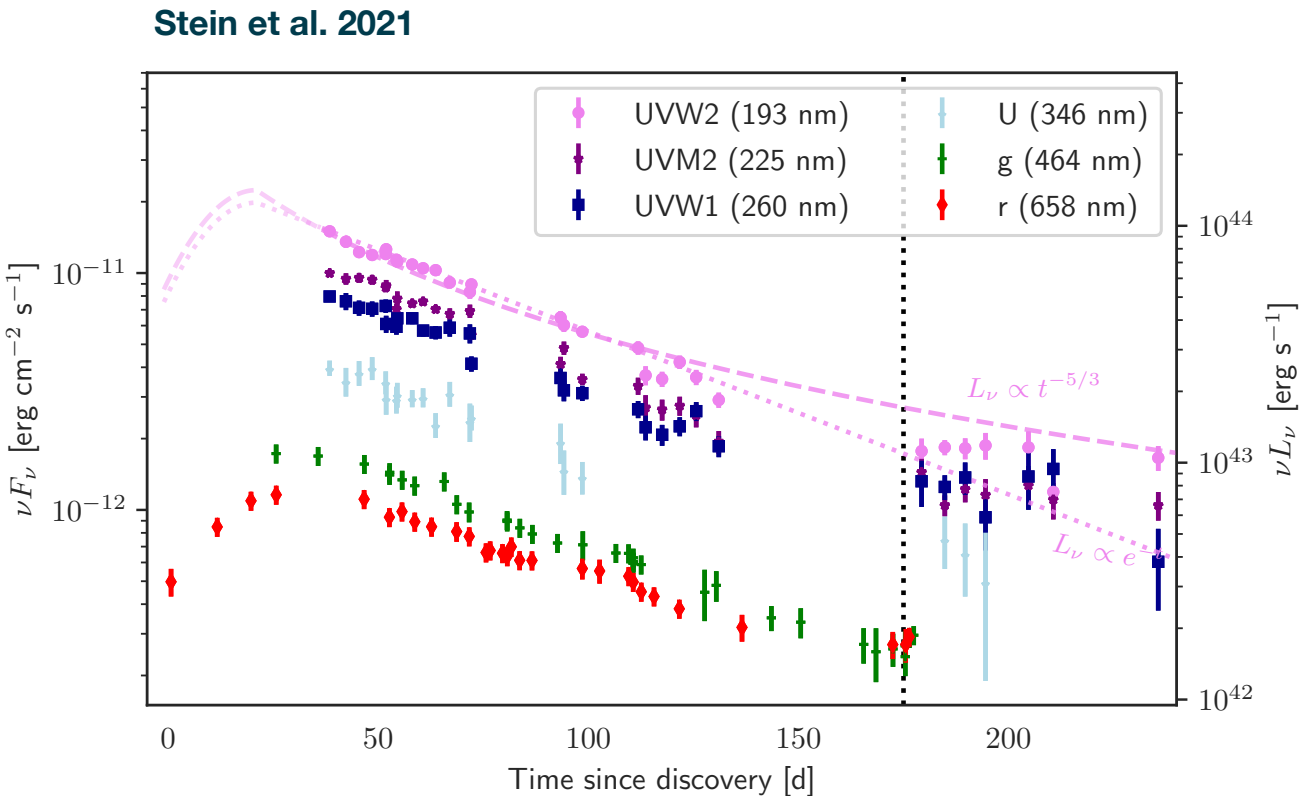
Featured in Physics | Editors' Suggestion

Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino

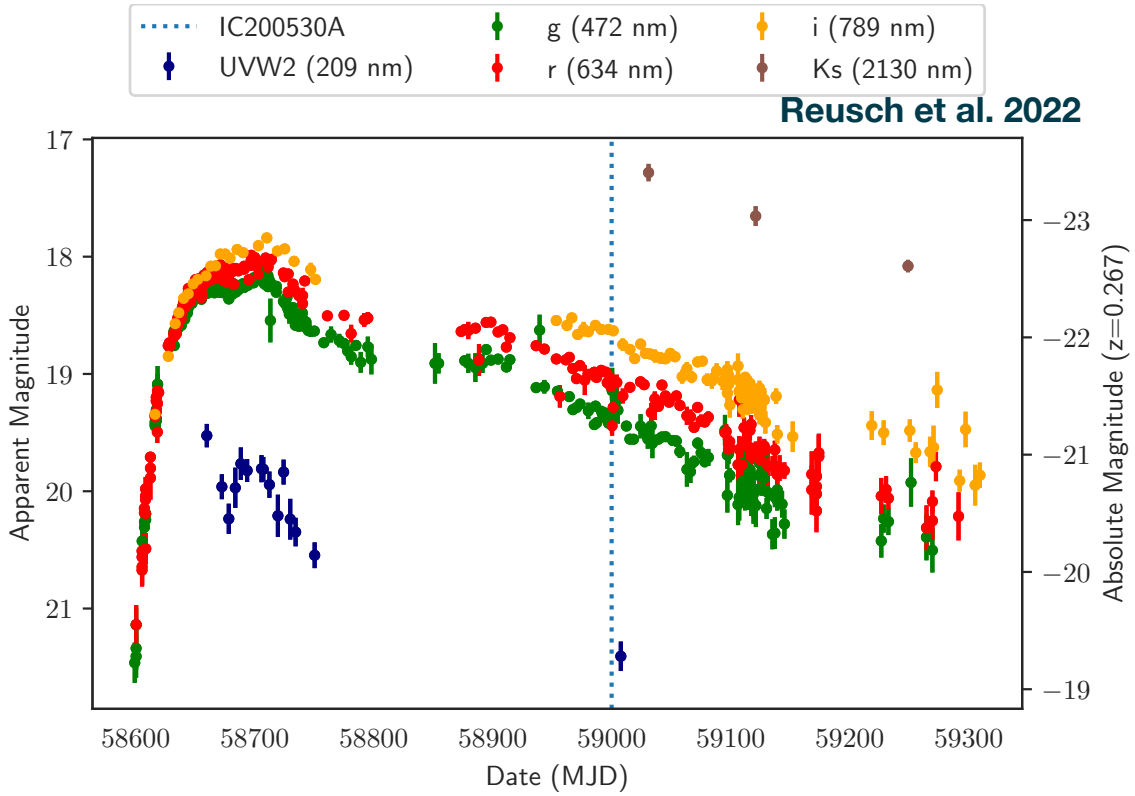
Simeon Reusch *et al.*
Phys. Rev. Lett. **128**, 221101 – Published 3 June 2022

Physics See Focus story: Neutrinos from a Black Hole Snack

From 24 neutrino follow-up campaigns -> Now two neutrino-TDEs



AT2019dsg



AT2019fdr

ZTF program uncovered 2 likely neutrino-TDEs out of 24 follow-up campaigns, both particularly bright

Probability of finding two bright TDE by chance with ZTF program: (0.034%=3.4σ)

See Cecilia's talk from this morning for more info on this

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What did we not find?

How likely are you to actually find a counterpart?

24 neutrino alerts

Account for astrophysical probability (typically ~50%)

Account for fraction of localisation observed (~60-90%)

Assume a population of neutrinos sources with a particular redshift evolution (e.g SFR)

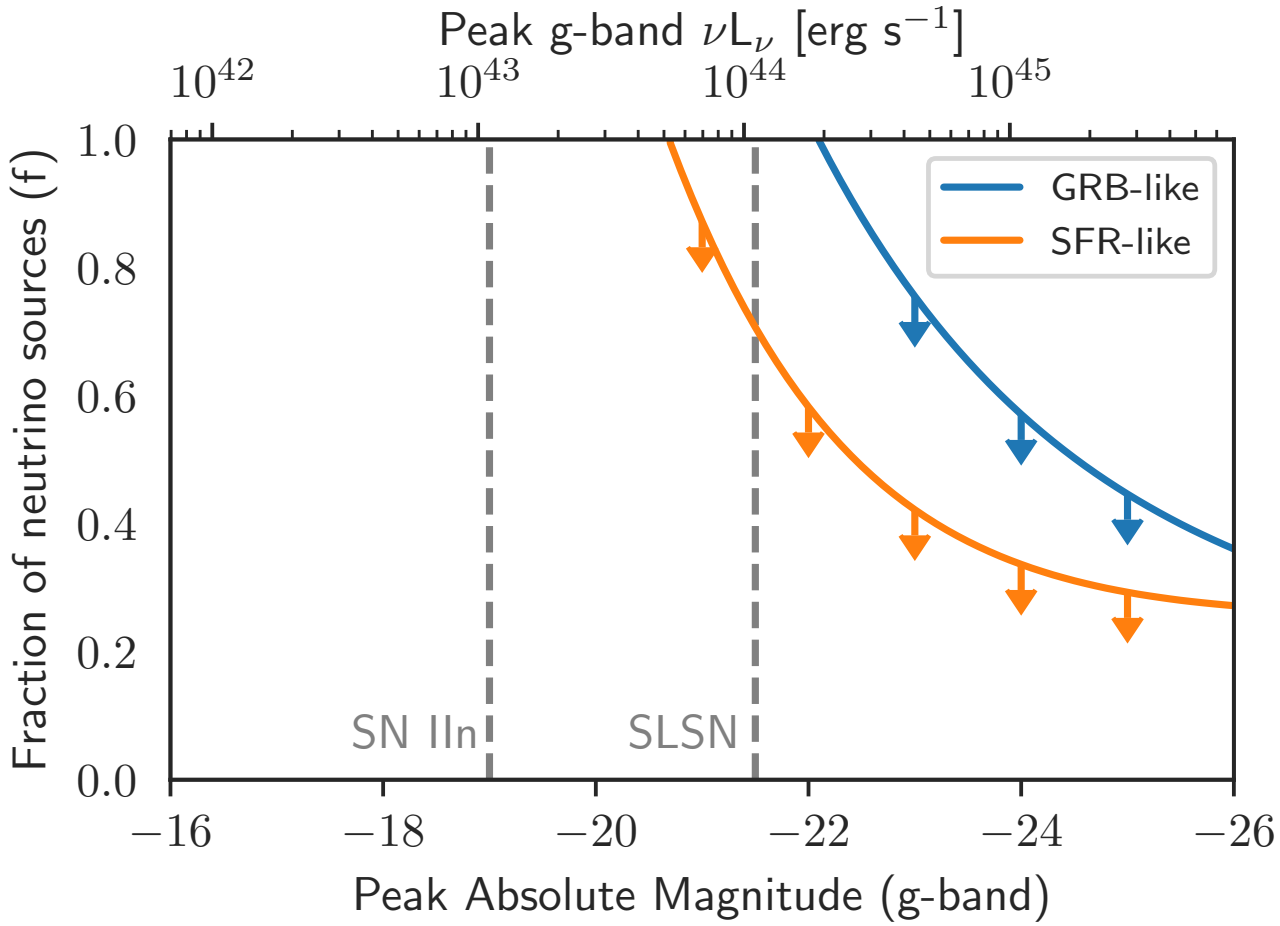
Estimate what fraction of sources would be detectable with ZTF for a given source source luminosity

Use our classification efficiency (~70% for faint sources)

Calculate probability to detect a counterpart in at least one of our campaigns

Limits on non-TDE neutrino source populations

Stein et al. 2022



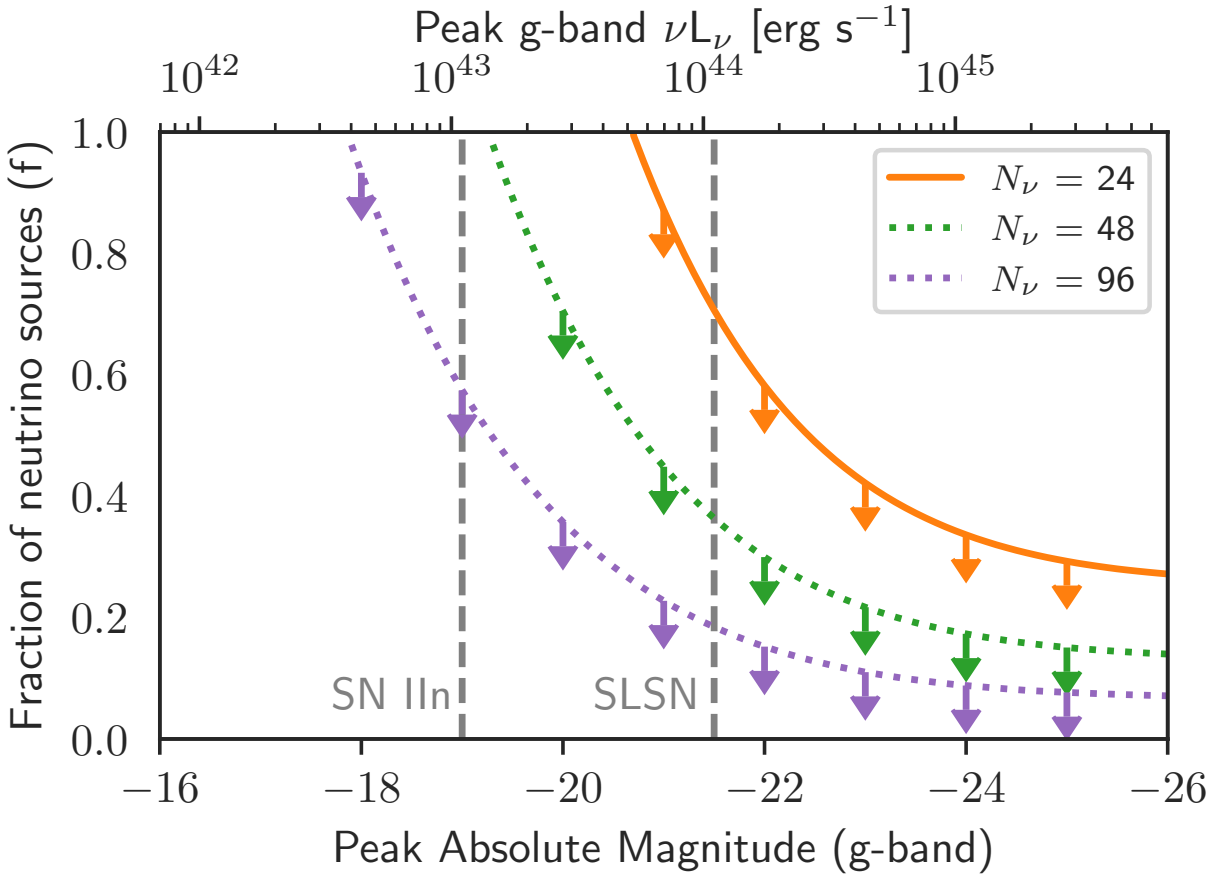
From 24 campaigns -> first constraints on the optical luminosity function of neutrino sources

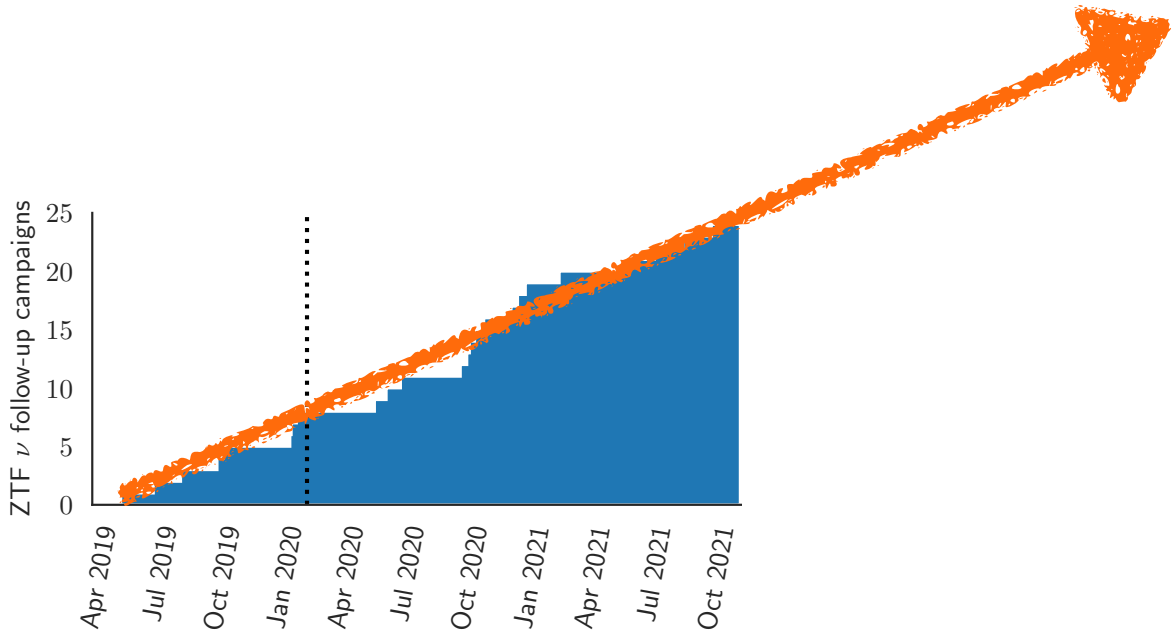
How can we do better in future?

How can we do better?

Stein et al. 2022

More campaigns





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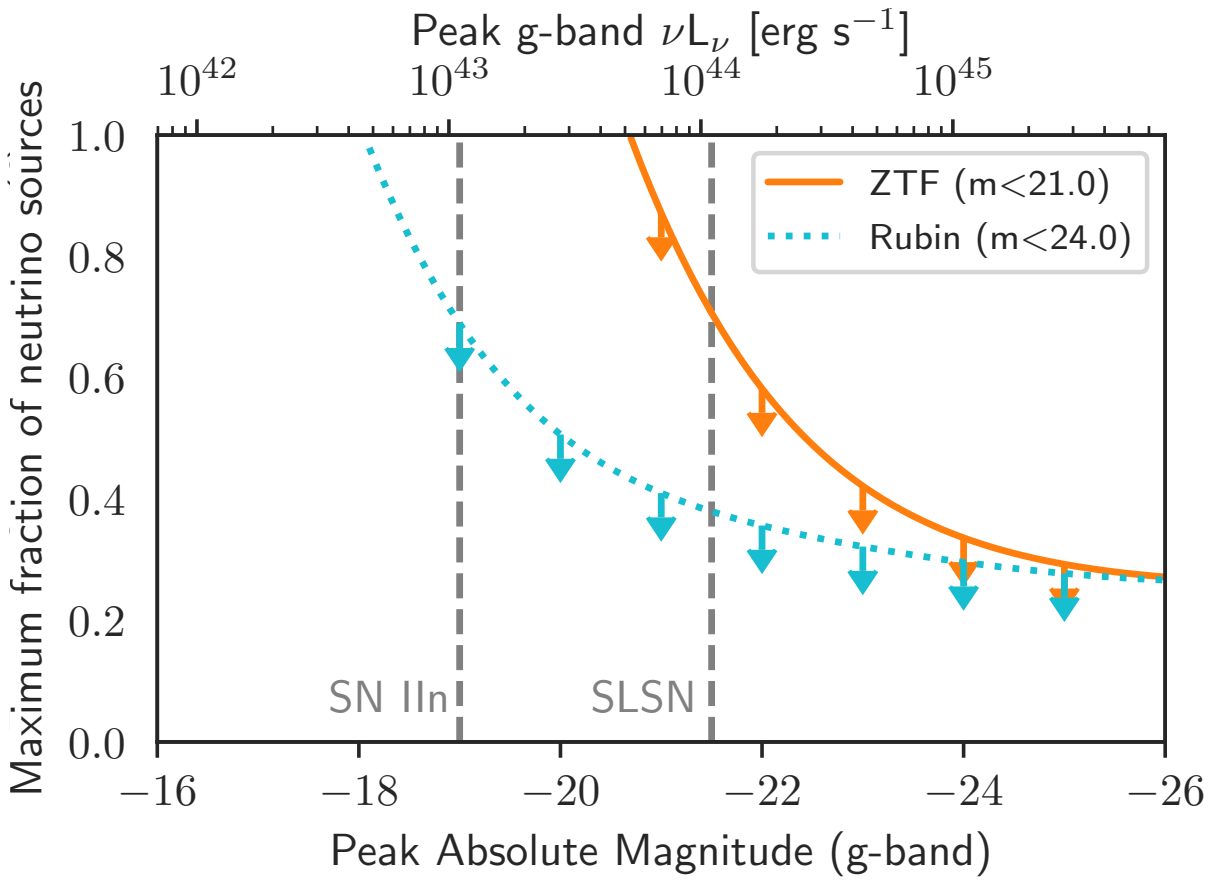
How can we do better?

Stein et al. 2022

Deeper campaigns



Credit: Bruno C. Quint

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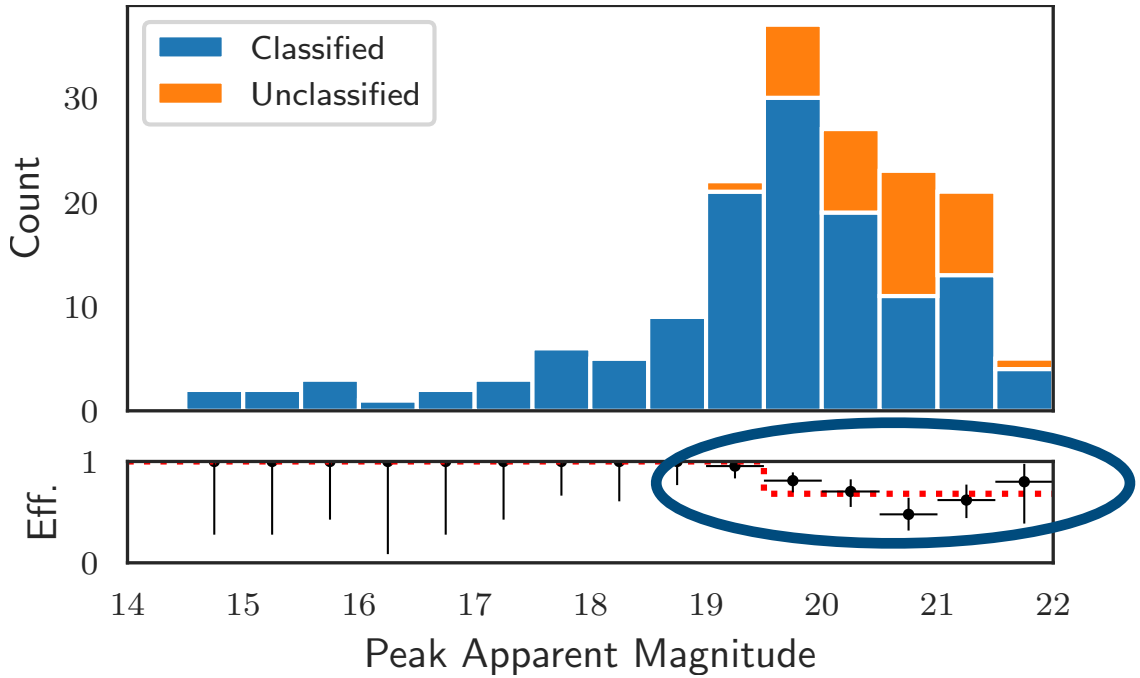
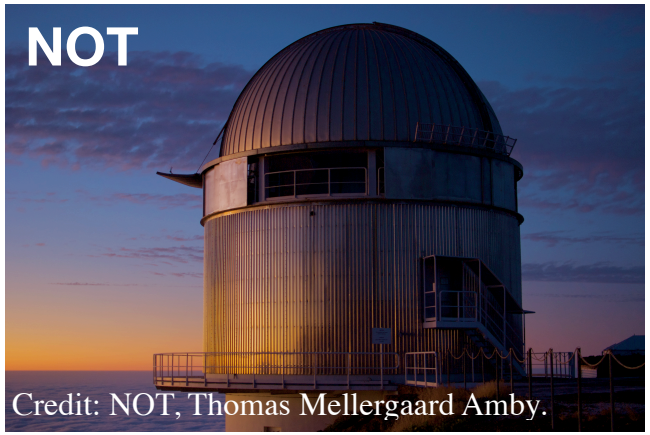
How can we do better?

Stein et al. 2022

Better completeness





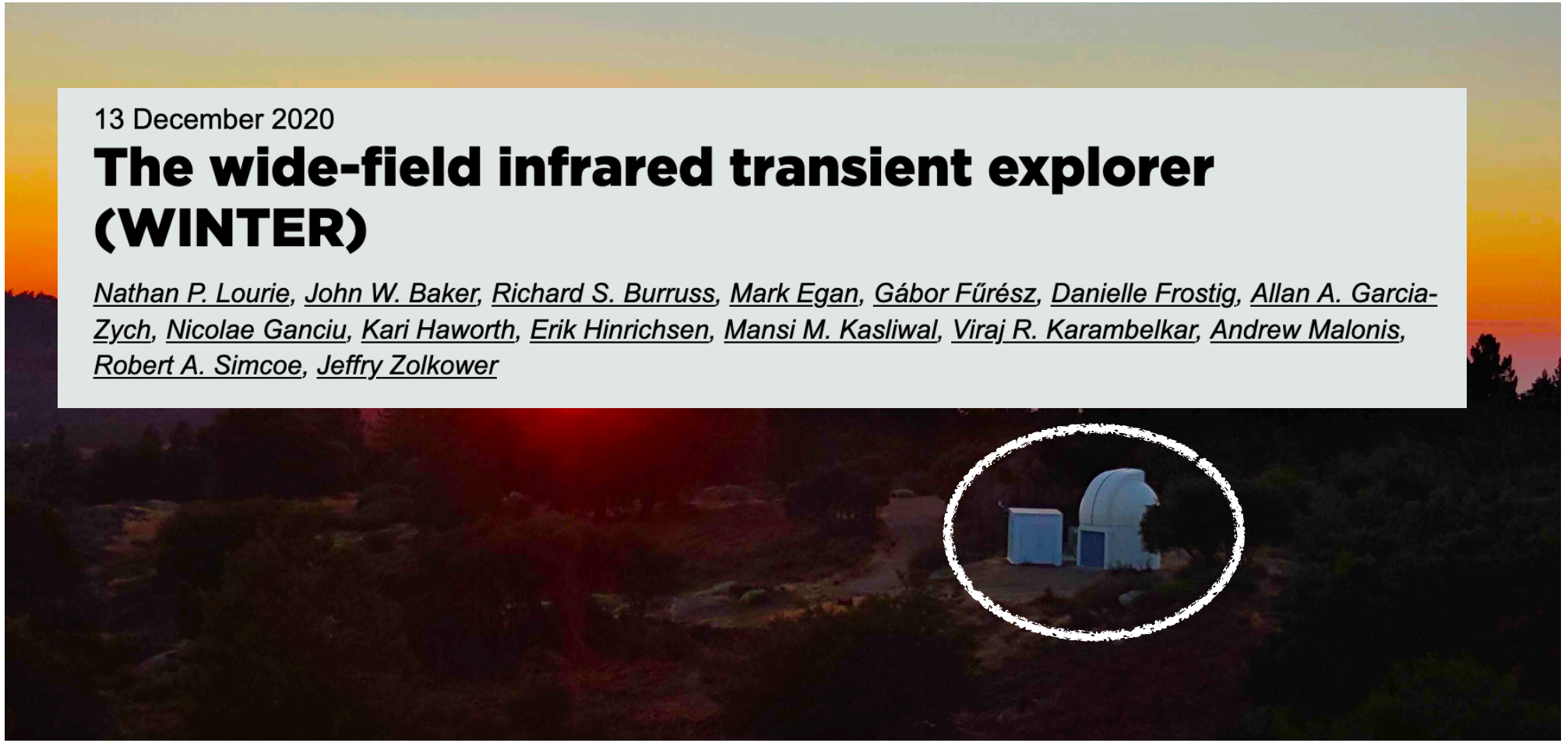
How can we do better?

New Wavelengths!

Credit: Robert Stein

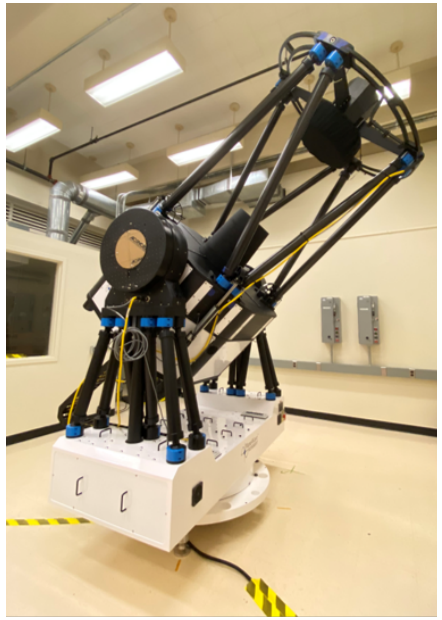
How can we do better?

New Wavelengths!



Credit: Robert Stein

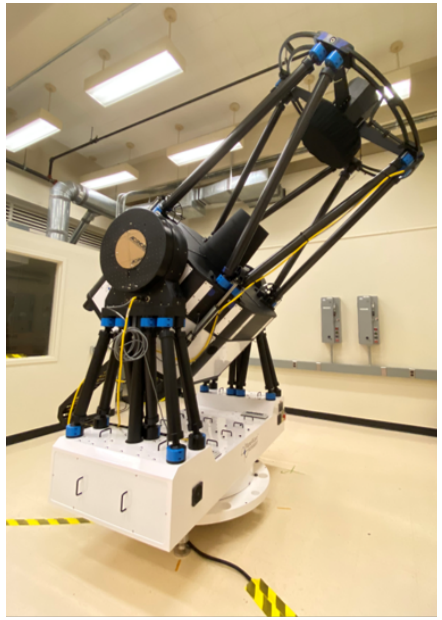
Introducing WINTER



J-band survey with ~monthly cadence

ToO program -> First dedicated IR neutrino follow-up program

Introducing WINTER



J-band survey with ~monthly cadence

ToO program -> First dedicated IR neutrino follow-up program

NIR is also great for kilonova searches ->
https://arxiv.org/abs/2110.01622

OPEN ACCESS

An Infrared Search for Kilonovae with the WINTER Telescope. I. Binary Neutron Star Mergers

Danielle Frostig[1], Sylvia Biscoveanu[1,2], Geoffrey Mo[1,2], Viraj Karambelkar[3], Tito Dal Canton[4], Hsin-Yu Chen[1,2], Mansi Kasliwal[3], Erik Katsavounidis[1,2], Nathan P. Lourie[1], Robert A. Simcoe[1] + Show full author list

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Citation Danielle Frostig *et al* 2022 *ApJ* **926** 152

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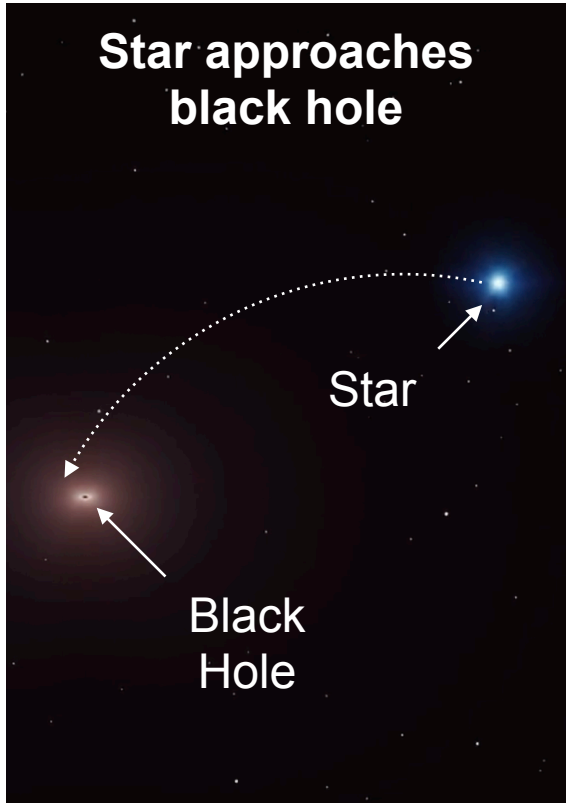
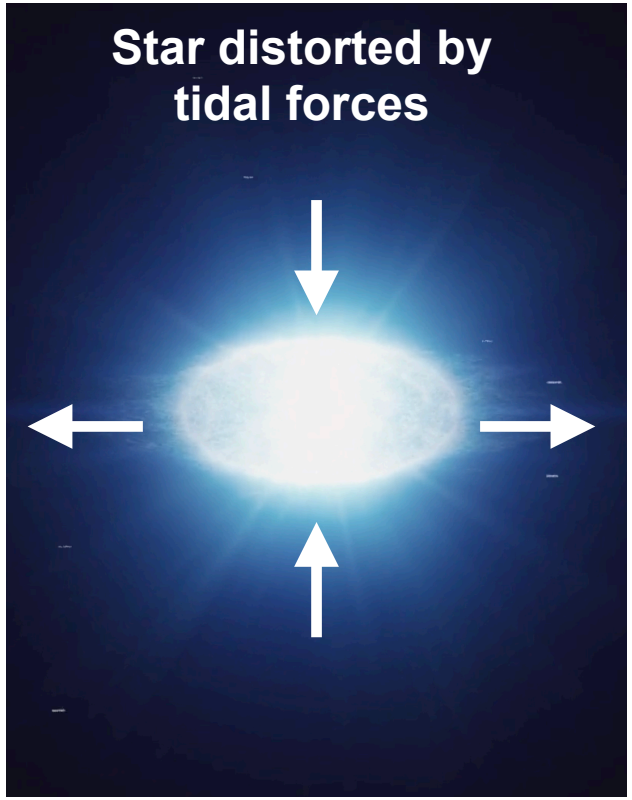
What are TDEs?

Credit: DESY/Science communication Lab





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Identifying AGN flares

Stein et al. 2022